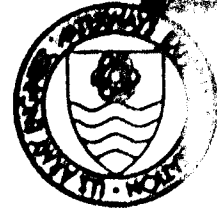


# LEVEL II



INSTRUCTION REPORT K-81-5

## USER'S GUIDE: COMPUTER PROGRAM FOR OPTIMAL DESIGN AND ANALYSIS OF PILE FOUNDATIONS (PILEOPT)

by

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March 1981

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20. ABSTRACT (continued).

within the limitations of pile loads and pile cap displacements specified by the user.



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## PREFACE

This user's guide documents a computer program called PILEOPT that can help in analyzing and designing pile foundation layouts. The program was developed as part of the applications support provided by the Automatic Data Processing (ADP) Center, U. S. Army Engineer Waterways Experiment Station (WES), to the U. S. Army Engineer Division, Lower Mississippi Valley (LMVD).

The program was coded by Dr. James L. Hill of Systems Engineering Consultants, Inc., Tuscaloosa, Ala., under contract to WES during the period September 1976-December 1979. Dr. Hill also prepared this user's guide.

Work on the program was coordinated with LMVD and the U. S. Army Engineer District, St. Louis (SLD). Liaison was maintained among LMVD, SLD, and WES by means of conferences and telephone conversations with Mr. Victor M. Agostinelli, LMVD, and Mr. Thomas J. Mudd and Mr. John Jobst, SLD, who defined the desired program modifications.

Mr. H. Wayne Jones of the Computer-Aided Design Group, ADP Center, WES, monitored the project under the supervision of Dr. N. Radhakrishnan, Special Technical Assistant, ADP Center. Mr. Donald L. Neumann was Chief of the ADP Center.

COL J. L. Cannon, CE, and COL N. P. Conover, CE, were Directors of WES during the development of the program modifications and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

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# CONTENTS

	<u>Page</u>
PREFACE . . . . .	1
CONVERSION FACTORS, INCH-POUND TO METRIC (SI)	
UNITS OF MEASUREMENT . . . . .	4
PART I: INTRODUCTION . . . . .	5
PART II: PROCEDURE FOR THE ANALYSIS OF PILE FOUNDATIONS . . . . .	7
Elastic Pile Constants 3-D System . . . . .	8
Linearly Varying Subgrade Modulus . . . . .	10
Fixity Coefficients . . . . .	12
Orientation of the Pile to the Foundations . . . . .	13
Coordinate Location of the Pile in the Foundation . . . . .	14
Loads and Displacements . . . . .	15
PART III: USE OF ZONES TO DEFINE PILE FOUNDATION . . . . .	16
PART IV: OPTIMIZATION OF PILE FOUNDATION DESIGN . . . . .	21
Phase I - Optimum Batter Slope Determination . . . . .	22
Optimization Variables Transformation . . . . .	24
The Nelder and Mead Direct Search Method . . . . .	25
Phase II - Determination of Pile Spacings and Pile Distribution . .	28
PART V: USER'S GUIDE FOR PROGRAM PILEOPT . . . . .	33
PART VI: NUMERICAL RESULTS . . . . .	41
Discussion of Results . . . . .	41
Extension of Optimization Strategy . . . . .	42
Discussion of Optimization Control Parameters . . . . .	42
Example No. 1 - Saul's Nine-Pile Problem . . . . .	44
Example No. 2 - Small Pile Foundation . . . . .	50
Example No. 3 - Dam Sill Monolith Foundation . . . . .	69
Example No. 4 - Lock Gate Monolith Foundation . . . . .	94
Example No. 5 - Abutment Monolith Foundation . . . . .	115
Example No. 6 - Pump Station Foundation . . . . .	133
REFERENCES . . . . .	161

CONVERSION FACTORS, INCH-POUND TO METRIC (SI)  
UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
inches	2.54	centimetres
inch-kips (force)	0.1129848	kilonewton-metres
kips (1000 lb force)	4.448222	kilonewtons
kips (force) per square inch	6.894757	megapascals
kips (force) per cubic inch	2.714471	megapascals per centimetre
square inches	6.4516	square centimetres

USER'S GUIDE: COMPUTER PROGRAM  
FOR OPTIMAL DESIGN AND ANALYSIS  
OF PILE FOUNDATIONS (PILEOPT)

PART I: INTRODUCTION

The U.S. Army Engineer Corps designs a great number of pile foundations for monolithic concrete structures. A typical structure may require a pile foundation of hundreds of displacement and/or end bearing piles. The selection and placement of the piles in the foundations must be such that limitations on pile forces and pile cap displacements are not exceeded. The restrictions must be satisfied for a large number of load cases (on the order of 10 to 20).

The computer program PILEOPT has been developed to aid the pile foundation designer in the Corps. The program PILEOPT is capable of analyzing a pile foundation using the method of Hrennikoff (Reference 1) as extended to three-dimensions by Saul (Reference 2) with the fixity coefficients as presented in the LMVD Pile Program Manual (Reference 3). In addition to analyzing, PILEOPT computes an optimal placement of the piles. The optimization of the pile foundation is based upon minimizing the cost of the piling within the limitations of pile loads and pile cap displacements.

The program PILEOPT has been used in this work to produce pile foundations for a set of realistic pile foundation design problems. These include pile foundations for a dam sill monolith, a lock gate monolith, an abutment monolith, and a pump station. The PILEOPT layouts are comparable to the actual designs for foundations for these structures. In all four of these cases, the pile layouts from PILEOPT contained fewer piles than used in the actual design. It appears that PILEOPT is successful in obtaining satisfactory pile layouts for large structures.

This report includes parts that present the analysis procedures used, a description of zone format, the strategy of the optimization, numerical results and a users guide for program PILEOPT. Part II contains the details of the analysis procedure for piles that is used in this work. Major portions of the procedure for the analysis of pile foundations were extracted from the "Report on Analysis of Pile Foundations" by Thomas J. Mudd of the St. Louis District of the Corps. The zone format, described in Part III, provides a way of describing the pile layout using a much smaller set of geometric parameters than the coordinates, angle to batter and batter slope for each pile. The optimization strategy is presented in Part IV and can best be described as a direct suboptimal sequential search for the best layout. The computer run times involved appear to make a more comprehensive search prohibitive. The numerical results of Part IV were all run on the Boeing Computer Service CDC-6600 computer system. Special thanks are due to John J. Jobst of the ADP Center of the St. Louis District of the Corps. He installed PILEOPT on the BCS computer and ran the sample problems. Part V contains user instructions for program PILEOPT.

## PART II: PROCEDURE FOR THE ANALYSIS OF PILE FOUNDATIONS\*

A general direct stiffness analysis of three-dimensional pile foundations has been presented by Saul (Reference 2) which is an expansion of the Hrennikoff method (Reference 1) from two to three dimensions. This method appears to be the most general, provided the designer has an understanding of matrix methods and structure-soil-pile interactions and an electronic computer is available to perform the computations. This method is an exact numerical analysis for the assumed soil-pile model. However, the designer must have an adequate representation of soil-pile interaction for input to the method.

A generalized model of the structure-pile system can be described as a rigid body supported by sets of springs which represent the actions of the pile forces on the structure when the structure is given unit displacements. It is assumed that the pile head loading for any single pile in a batter group may be resolved into a combination of axial load, bending moment, shear and torque. Also, each of these components can be represented by a proper spring constant. The results can be added vectorially to obtain the total movement of the pile head. This method only considers the effect the piles have on the pile cap at the top of the pile, i.e., each pile can be replaced by the proper elastic spring restraints at the pile cap. The assumptions required by this method are:

- a. A rigid piling cap
- b. Elastic behavior of the system

\*Major portions of this Part are extracted from the "Report on Analysis of Pile Foundations", by Thomas J. Mudd, Structural Conference, LMVD, 23-24 September 1969.

This method can also account for:

- (1) Any degree of fixity of any pile with the pile cap
- (2) Piles with different bending stiffness about their principal axes.
- (3) Any degree of linear (elastic) torsional, axial or lateral resistance of any pile in the foundation.
- (4) Any position and batter of piles in the foundation.
- (5) Piles of different sizes or materials in the foundation.

### Elastic Pile Constants 3-D System

Each pile has six degrees of freedom in a three-dimensional system; two lateral, one axial, two rotations, and one twist. The forces and displacements along the pile axis are shown in Fig. II.1 in which local axes  $u_1$  and  $u_2$  are principal axes of inertia and axis  $u_3$  coincides with the longitudinal axis of the piling. The local axis ( $u_1, u_2, u_3$ ) for a pile are shown in relation to the global (or foundation) axes ( $U_1, U_2, U_3$ ) in Fig. II.2. The pile is located at a point in the global coordinate system by the coordinates ( $UP_1, UP_2, UP_3$ ). The pile forces can be related to the pile displacements by the expression

$$\{f\}_i = \{B\}_i \{x\}_i \quad (1)$$

such that  $b_{ij}$  are the individual pile stiffness influence coefficients called the elastic pile constants. The  $\{B\}_i$  matrix for a three dimensional system can be defined for the  $i$ -th pile as

$$\{B\}_i = \begin{Bmatrix} b_{11} & 0 & 0 & 0 & b_{15} & 0 \\ 0 & b_{22} & 0 & b_{24} & 0 & 0 \\ 0 & 0 & b_{33} & 0 & 0 & 0 \\ 0 & b_{42} & 0 & b_{44} & 0 & 0 \\ b_{51} & 0 & 0 & 0 & b_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & b_{66} \end{Bmatrix} \quad (2)$$

The elastic pile constants are defined as follows:

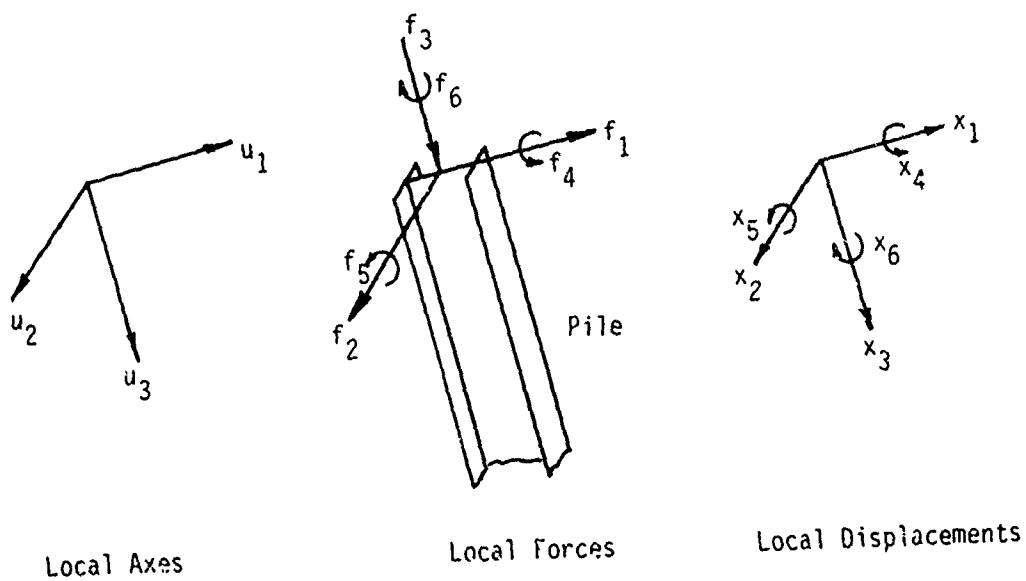


fig.II.1 Local Axes, Forces and Displacements of the Pile

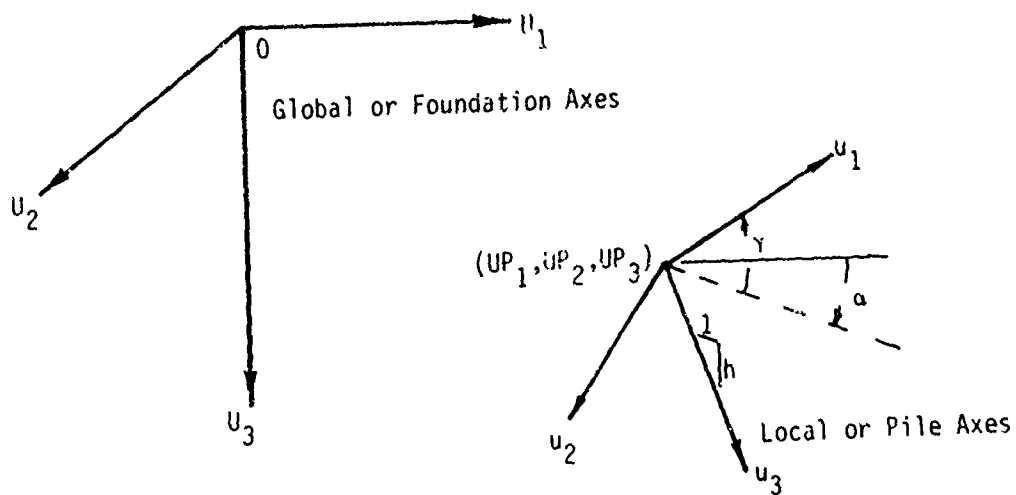


Fig.II.2 Global and Local Axes

- $b_{11}$  - is the force required to displace the pile head a unit distance along the  $u_1$  axis - FORCE/LENGTH
- $b_{22}$  - is the force required to displace the pile head a unit distance along the  $u_2$  axis - FORCE/LENGTH
- $b_{33}$  - is the force required to displace the pile head a unit distance along the  $u_3$  axis - FORCE/LENGTH
- $b_{44}$  - is the moment required to displace the pile head a unit rotation around the  $u_1$  axis -  $\frac{\text{FORCE-LENGTH}}{\text{RADIAN}}$
- $b_{55}$  - is the moment required to displace the pile head a unit rotation around the  $u_2$  axis -  $\frac{\text{FORCE-LENGTH}}{\text{RADIAN}}$
- $b_{66}$  - is the torque required to displace the pile head a unit rotation around the  $u_3$  axis -  $\frac{\text{FORCE-LENGTH}}{\text{RADIAN}}$
- $b_{15}$  - is the force along the  $u_1$  axis required to cause a unit rotation of the pile head around the  $u_2$  axis -  $\frac{\text{FORCE}}{\text{RADIAN}}$
- $b_{24}$  - is the force along the  $u_2$  axis required to cause a unit rotation of the pile head around the  $u_1$  axis -  $\frac{\text{FORCE}}{\text{RADIAN}}$  NOTE: The sign is negative
- $b_{51}$  - is the moment around the  $u_2$  axis required to cause a unit displacement of the pile head along the  $u_1$  axis -  $\frac{\text{FORCE-LENGTH}}{\text{LENGTH}}$
- $b_{42}$  - is the moment around the  $u_1$  axis required to cause a unit displacement of the pile head along the  $u_2$  axis -  $\frac{\text{FORCE-LENGTH}}{\text{LENGTH}}$  Note: The sign is negative.

The element for the  $(B)_i$  matrix are symmetric as follows:

$$\begin{aligned} b_{15} &= b_{51} \\ b_{24} &= b_{42} \end{aligned}$$

#### Linearly Varying Subgrade Modulus

When it is assumed that the lateral subgrade modulus varies linearly with depth, the pile constants for a three-dimensional system can be derived as follows:

$$\text{If } T_x = \sqrt[5]{\frac{EI}{n_h} x} \qquad T_y = \sqrt[5]{\frac{EI}{n_h} y}$$

Then

$$b_{11} = K_1 \frac{EI_x}{T_x^3}$$

$$b_{22} = K_1 \frac{EI_y}{T_y^3}$$

$$b_{33} = K_2 \frac{AE}{L}$$

$$b_{44} = K_3 \frac{EI_x}{T_x^3}$$

$$b_{55} = K_3 \frac{EI_y}{T_y^3}$$

$$b_{66} = K_4 \frac{JG}{L}$$

$$b_{15} = K_5 \frac{EI_x}{T_x^2}$$

$$b_{24} = -K_5 \frac{EI_y}{T_y^2}$$

$$b_{51} = K_6 \frac{EI_x}{T_x^2}$$

$$b_{42} = -K_6 \frac{EI_y}{T_y^2}$$

Where

$E$  = Modulus of Elasticity

$I$  = Moment of Inertia

$n_h$  = Lateral Subgrade Modulus

$A$  = Cross-Sectional Area of Pile

$L$  = Length of Pile

$G$  = Torsion Modulus

$K_1$  = Lateral Fixity Coefficient

$K_2$  = Pile Resistance

$K_3$  = Rotational Fixity Coefficient

$K_4$  = Coefficient for Torsion

$K_5$  = Fixity Coefficient

$K_6$  = Fixity Coefficient

### Fixity Coefficients

The constants,  $K_i$ , can be defined as the degree of rigidity and depend on such variables as the pile head fixity and the distribution of load from the pile to the soil axially and torsionally. Values of the  $K$ 's can be derived for various degrees of fixity.

Knowing the degree of fixity, the following values of  $K$  can be derived for a lateral subgrade modulus that varies linearly with depth:

Degree of Fixity (DF)	Fixity Coefficients for Linear Subgrade Modulus					
	$K_1$	$K_2$	$K_3$	$K_4$	$K_5$	$K_6$
1.0	1.0765	1.0 for bear-	1.4988	Torsion (as-	0.9990	0.9990
0.9	1.0099	ing or 2.0	1.3489	sumed 0.0	0.8991	0.8991
0.8	0.9433	for fric-	1.1990	by some	0.7992	0.7992
0.7	0.8767	tion piles	1.0491	designers)	0.6993	0.6993
0.6	0.8101	in compres-	0.8993		0.5994	0.5994
0.5	0.7435	sion. For	0.7494		0.4995	0.4995
0.4	0.6770	piles in	0.5995		0.3996	0.3996
0.3	0.6104	tension	0.4496		0.2997	0.2997
0.2	0.5438	the value	0.2998		0.1998	0.1998
0.1	0.4773	should be	0.1499		0.0999	0.0999
0.0	0.4107	reduced.	0.0		0.0	0.0
		Suggest 1/2				
		of value				
		for com-				
		pression				
		piles				

The value of DF, degree of fixity of a pile into the cap (expressed as a fraction), must be selected with a full understanding of the conditions that must be met for a pile which is assumed to be fixed to actually be fixed.

The fixity of the pile, DF, depends to a great extent on the pile's embedment into the pile cap. A pretensioned prestressed concrete pile is not fully fixed unless the extension of the concrete of the pile into the cap is at least as long as the bond development length of the prestressing strands. Further, the pile cannot develop the full moment capacity at the bottom of the cap. Any strand extension distance beyond the end of the pile does not contribute to the bond development distance because the strand elongation needed to develop the strand prestress will cause excessive cracking and loss of rigidity of the concrete. However, a posttensioned concrete pile can be considered fully fixed with less embedment than a pretensioned pile if the tendon(s) are tensioned to the cap after the cap is placed. A non-prestressed

concrete pile can be considered fully fixed by a bar extension equal to the bond development length.

### Orientation of the Pile to the Foundation

In a three-dimensional system the pile may be located at a rotated position to the foundation axis and may be battered. Its position in the pile cap is fully defined by the clockwise angle  $\alpha_i$  to the direction of batter and the batter slope  $h_i$  as shown in Fig. 11.2. The principal axis of the  $i$ -th pile, where  $I_x \neq I_y$ , should coincide with the  $\alpha_i$ . For pile  $i$ , the local (pile) axes are related to the global (foundation) axes by the transformation matrix  $\{A\}_i$ .

$$\{A\}_i = \begin{Bmatrix} a & 0 \\ 0 & a \end{Bmatrix}$$

where

$$\{a\}_i = \begin{Bmatrix} \cos \gamma \cos \alpha & -\sin \alpha & \sin \gamma \cos \alpha \\ \cos \gamma \sin \alpha & \cos \alpha & \sin \gamma \sin \alpha \\ -\sin \gamma & 0 & \cos \gamma \end{Bmatrix}$$

$h_i$  = batter ( $h_i$  vertical on 1 horizontal)

$\alpha_i$  = clockwise angle to the batter and/or principal axis

$\gamma_i$  =  $\arctan h_i$

The local components of pile forces,  $\{f\}$ , are related to the global components of pile forces by

$$\{F\}_i = \{A\}_i \{f\}_i \quad \text{or} \quad \{f\}_i = \{A\}_i^T \{F\}_i$$

Likewise the local  $\{x\}_i$  and global  $\{X\}_i$  components of pile displacement are related by

$$\{X\}_i = \{A\}_i \{x\}_i \quad \text{or} \quad \{x\}_i = \{A\}_i^T \{X\}_i$$

Expressing equation (1) in terms of global components gives

$$\{F\}_i = \{A\}_i \{B\}_i \{A\}_i^T \{X\}_i$$

which is the relationship of the pile forces to pile displacements in components along the global or foundation axes.

### Coordinate Location of the Pile in the Foundation

Pile  $i$  is located in the global coordinate system as shown in Fig. II.2. The pile cap loads  $\{Q\}$  and displacements  $\{D\}$  are specified with respect to the global axes. The forces  $\{F\}_i$  on the pile are equivalent to a set of forces  $\{q\}_i$  at the coordinate center of the pile cap given by

$$\{q\}_i = \{C\}_i \{F\}_i$$

in which the matrix  $\{C\}_i$  is

$$\{C\}_i = \begin{Bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -UP_3 & UP_2 & 1 & 0 & 0 \\ UP_3 & 0 & -UP_1 & 0 & 1 & 0 \\ -UP_2 & UP_1 & 0 & 0 & 0 & 1 \end{Bmatrix}$$

where  $(UP_1, UP_2, UP_3)$  are the coordinates of the pile in the global coordinate system.

The displacements of the pile,  $\{X\}_i$  can be obtained from the displacements of the pile cap,  $\{D\}$  because of the assumption of the pile cap as rigid. This relation is

$$\{X\}_i = \{C\}_i^T \{D\}$$

Thus the equivalent force at the coordinate center due to pile  $i$  is

$$\{q\}_i = \{C\}_i \{A\}_i \{B\}_i \{A\}_i^T \{C\}_i^T \{D\}$$

For equilibrium, the sum of the pile forces,  $\{q\}_i$  must sum to the external load on the pile cap  $\{Q\}$  as

$$\{Q\} = \sum_{i=1}^n \{q\}_i$$

where  $n$  = the number of piles. Substitution of the expression for  $\{q\}_i$  yields

$$\{Q\} = \sum_{i=1}^n \{C\}_i \{A\}_i \{B\}_i \{A\}_i^T \{C\}_i^T \{D\}$$

or

$$\{Q\} = \{S\} \{D\}$$

where  $\{S\}$  is the stiffness matrix for the pile foundation. The stiffness matrix,  $\{S\}$ , is given by

$$\{S\} = \sum_{i=1}^n \{C\}_i \{A\}_i \{B\}_i \{A\}_i^T \{C\}_i^T$$

The remainder of the analysis involves inversion of  $\{S\}$  and back substitution to calculate pile cap displacements, pile head displacements, local pile forces and global pile forces.

#### Loads and Displacements

The displacements of the pile cap can be found by inverting the foundation stiffness matrix  $\{S\}$  and multiplying it by the external load matrix  $\{Q\}$  or

$$\{D\} = \{S\}^{-1} \{Q\}$$

Once the foundation displacements are known the displacements of pile  $i$  along the local axes can be found by

$$\{x\}_i = \{A\}_i^T \{C\}_i^T \{D\}$$

Finally, the local forces in each pile can be found from equation (1) where

$$\{f\}_i = \{B\}_i \{x\}_i$$

The pile forces along the global or foundation axes are given by

$$\{F\}_i = \{A\}_i \{f\}_i$$

This completes the analysis of the pile foundation.

### PART III: USE OF ZONES TO DEFINE PILE FOUNDATION

The base of the pile cap is a collection of a number of geometric "zones". A typical rectangular zone is shown in Fig. III.1. The "zones" are areas of the pile cap base that satisfy the following restrictions:

1. A zone is a rectangular or circular area that is parallel to the  $U_1$ - $U_2$  plane. The zones may be of different elevations.
2. A zone is located by specifying the coordinates of the corner (C) of the zone that has minimum  $U_1$  and  $U_2$  coordinates.
3. The zone may be rotated in the global  $U_1$ - $U_2$  plane.
4. All piles in a zone are identical. The piles in a zone are from the same group.
5. The piles in a zone can only occupy points on a rectangular grid that is parallel to the sides of the zone.
6. A zone has a border region in which no piles may be placed. The width of the borders is optional as indicated in Fig. III.1.
7. The batter of piles in the zone is such that
  - a. The plane of batter (or the plane in which the piles are battered) is the same for all piles in zone. The plane of batter is vertical and is specified by the angle that it makes with a side of the zone.
  - b. The batter slope of all piles in a row (or column) of a zone will be the same.
  - c. A pattern for battering the piles is specified by three integer parameters IRC, NPB1, and NPB2. IRC is either 1 or 2. If IRC = 1 the batter slope changes in the  $U_1$  direction of the grid. For IRC = 2 the batter slope changes in the  $U_2$  direction. NPB1 is the number of rows (columns) in which the batter slope is held constant at  $H_1$  before changing to  $H_2$  for the next NPB2 rows (columns). This pattern of NPB1 rows then NPB2 rows is repeated until the batter slopes of all piles in the zone are specified. If  $H_2$  is to be in the opposite direction then  $H_1$  and  $H_2$  should be of different algebraic sign (+ or -).

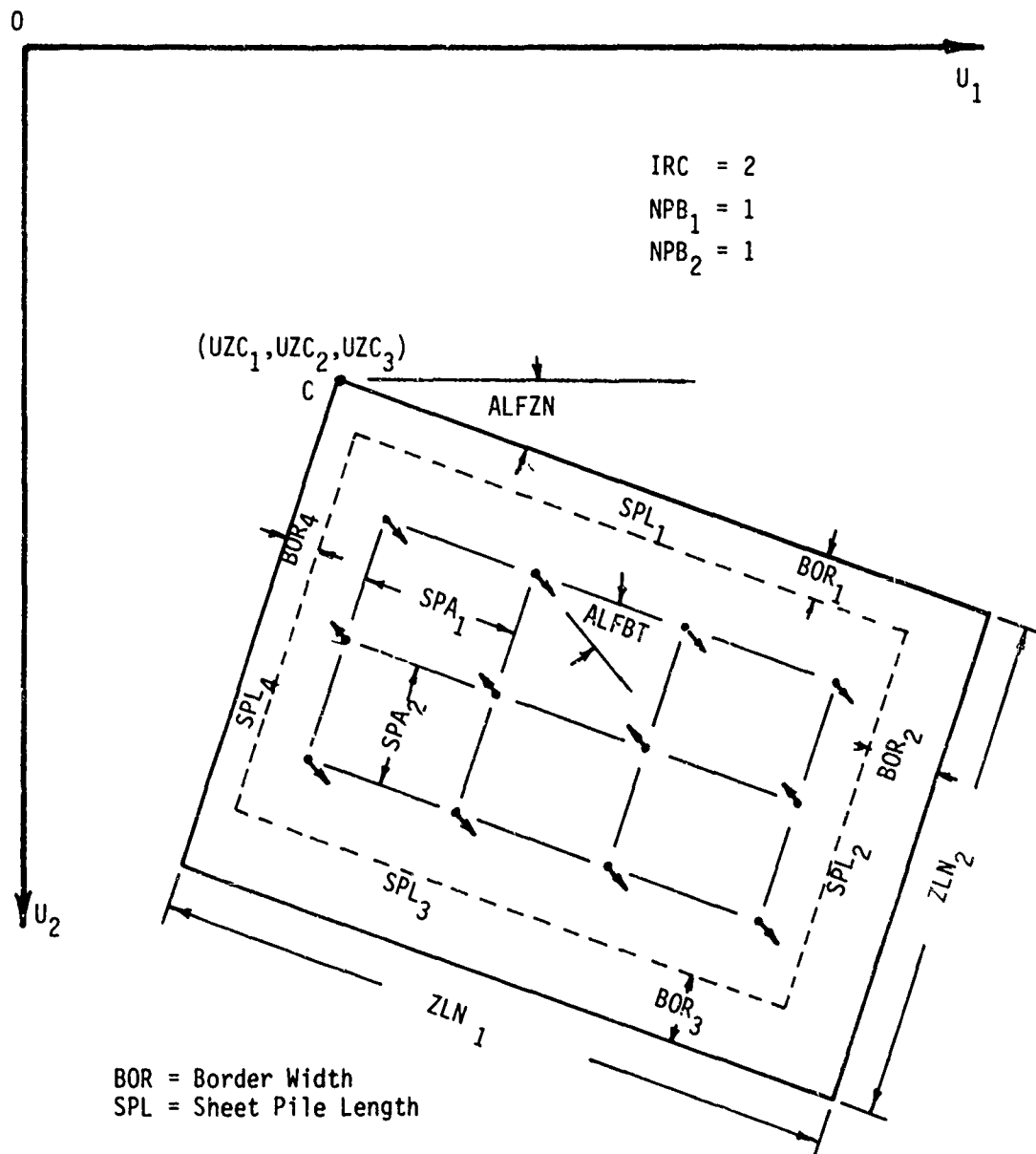


Fig. III.1 Typical Rectangular Zone

- d. The direction of the principal axes of all piles in a zone will be parallel and perpendicular to the plane of batter.
8. Sheet piles of any length can be placed on the inner border (dotted line) of any side. If piles interfere with sheet piling, the interfering rows are offset one-half spacing. If piles still interfere with sheet piling after they have been offset, they are deleted.
9. Zones can also be circular. A typical circular zone is presented in Fig III.2.
10. The program is capable of handling repeated zones that have various symmetry options. A repeated zone is defined relative to a parent zone. The parent zone must be defined before a zone can be designated as a repeat of it. The repeated zone can be arbitrarily placed and rotated just as the parent zone can. The symmetry option is selected by a parameter called IFLIP. The four choices for IFLIP of a repeated zone are given below. The symmetry options are illustrated in Fig III.3. Repeated circular zones can only be flipped about the 1 - axis (IFLIP =1).

Table of Symmetry Options for Repeated Zones

<u>IFLIP</u>	<u>Symmetry Option of Repeated Zone</u>
0	Repeated zone is a displaced version of the parent zone.
1	Repeated zone is obtained by flipping the pile layout and borders about an axis parallel to the side of length $ZLN_1$ (1-axis).
2	Repeated zone is a flip of the parent zone about an axis parallel the side of length $ZLN_2$ (2-axis).
3	Repeated zone is obtained by flipping parent zone about the the 1-axis and then about the 2-axis.

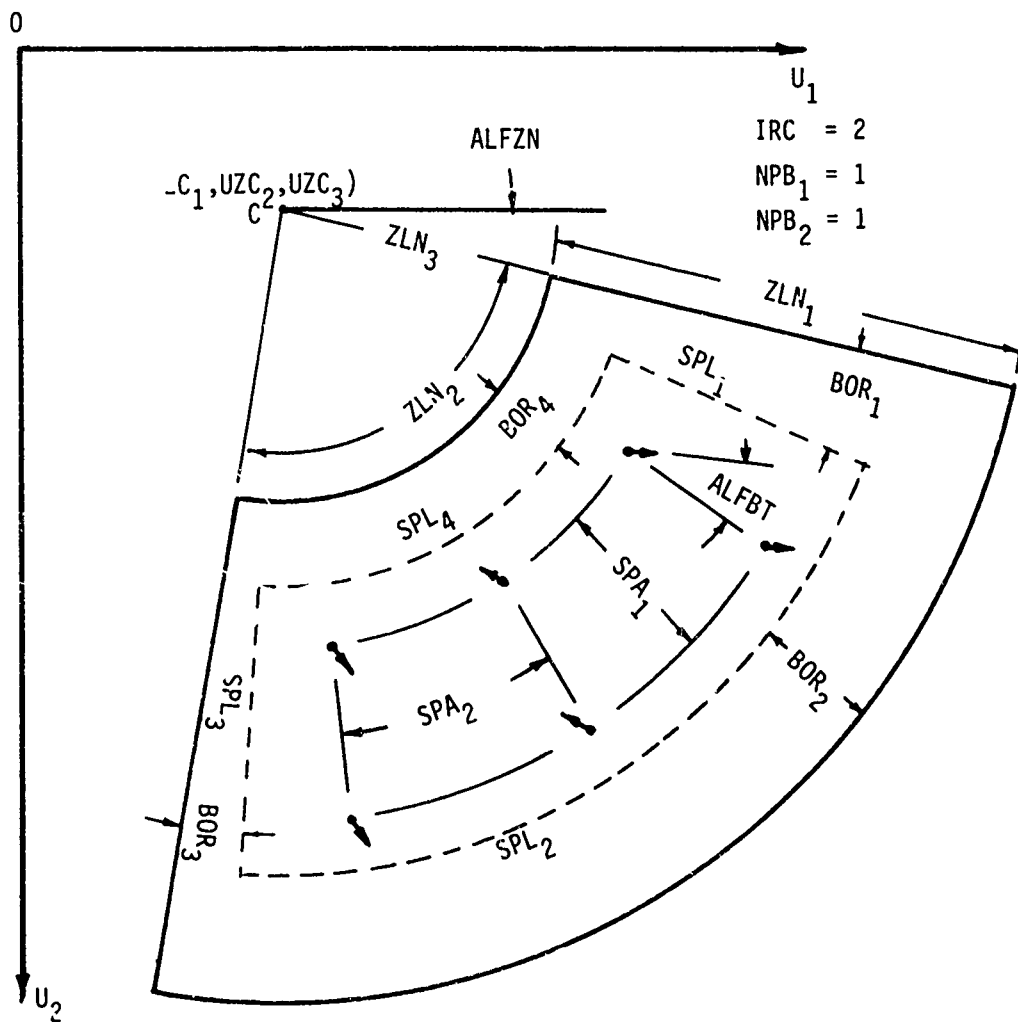


Fig. III.2 Typical Circular Zone

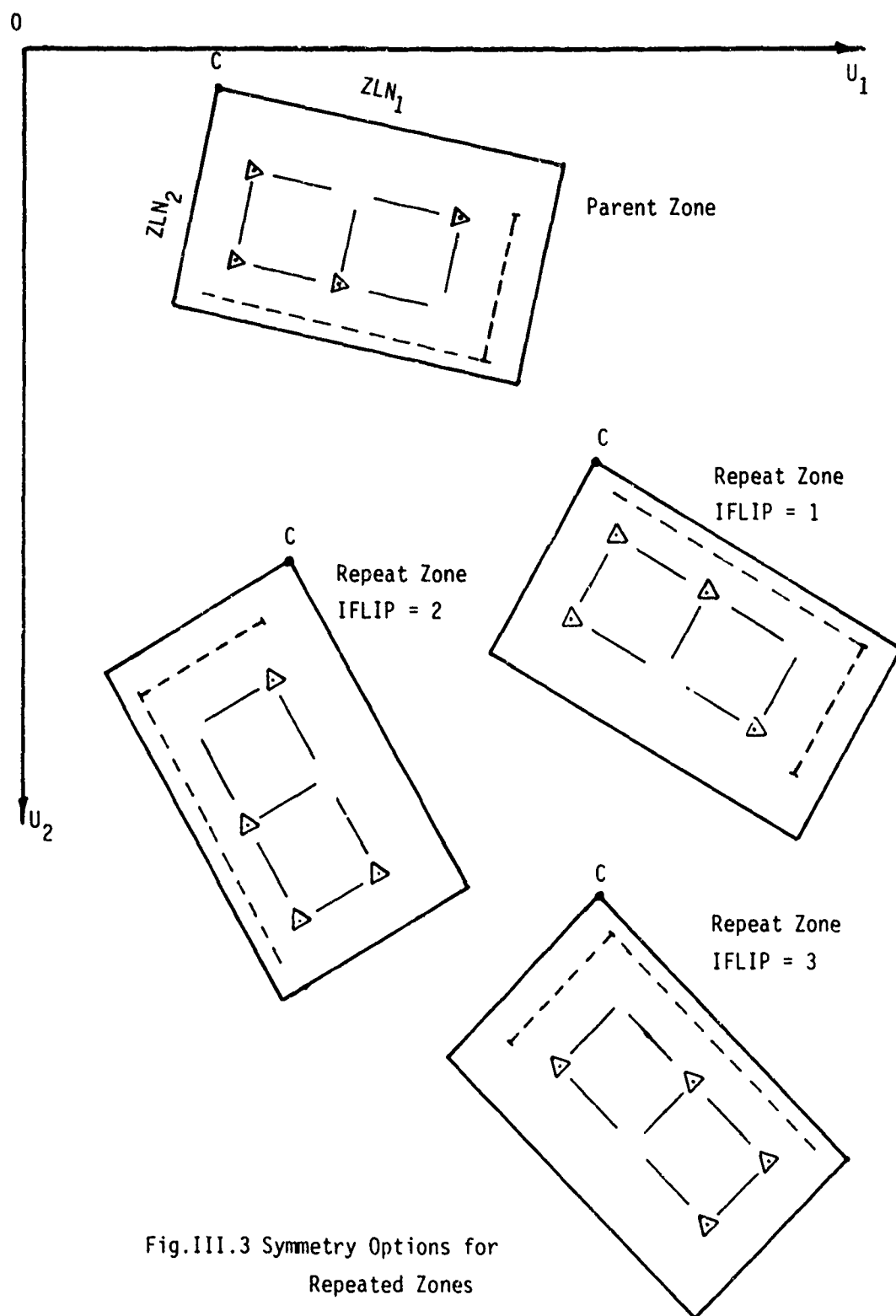


Fig.III.3 Symmetry Options for Repeated Zones

#### PART IV: OPTIMIZATION OF PILE FOUNDATION DESIGN

The method implemented to optimize the pile foundation design is divided into two separate phases. In the first phase the optimum batter slopes are calculated. These optimum batter slopes are defined by the requirement that a weighted sum of the pile load factors is minimized. With the optimum batter slopes determined, the best values of the spacings and the distribution of piles are calculated in the second phase. Piles are placed at all grid points for a set of spacings, the foundation is analyzed and the distribution of piles is determined by selectively removing piles until further deletion results in violation of either load or displacement constraints. The spacings are changed by incrementing them one at a time to determine the best value of each spacing. The load constraints are that load factors cannot exceed the overstress factor that is allowed for the given loading. The displacement components of any point in the pile cap base are limited by allowable displacements specified for the three global directions.

Thus the optimization process is very sequential. First the optimum batter slopes are calculated, then the spacing in the  $U_1$ -direction of the first zone, then spacing in the  $U_2$ -direction for the first zone and so on until the spacings of all zones have been obtained. The distribution of retained piles is determined at every set of spacings. From the trial layouts considered, the design of minimum cost is selected. This sequential search strategy assumes that the layout parameters of batter slopes, spacings and distribution do not interact strongly. Although this is not always true, this scheme has yielded encouraging results in several problems. Even with this strategy, significant computer time is required for a realistic design problem. The sequential strategy could be

extended by calculating new batter slopes after the spacings and distribution have been obtained. Hopefully, with better batter slopes, additional piles could be deleted. The main disadvantage in this type of continuation would be the additional computer resources required. The limited strategy adopted is a compromise between computer run time and the possible additional cost savings in the design.

#### Phase I - Optimum Batter Slope Determination

The calculation of optimum batter slopes is begun by placing piles at all grid points of the zones. The grids for the zones are defined by the initial values of the spacings for the zones and the other geometric zone parameters. The objective of the optimum batter slope calculation is to minimize a weighted sum of pile load factors for all piles.

The local forces in the pile for any load case, LC, and soil condition, SC, are  $FL(1), FL(2), \dots, FL(6)$ . The allowable forces in the pile for the soil condition are given as:

CALLOW = Allowable compressive load

TALLOW = Allowable tension load

FA = Allowable axial load in combined axial and bending loading

FB4, FB5 = Allowable bending moments about the minor and major principal axes of the pile, respectively

The following pile load factors are defined:

Compression pile  $FL(3) > 0$

$$CPLF = FL(3)/CALLOW$$

Tension pile  $FL(3) < 0$

$$TPLF = -FL(3)/TALLOW$$

Axial pile load factor

$$APLF = \text{Max}(CPLF, TPLF)$$

Bending pile load factor

$$BPLF = |FL(4)|/FB4 + |FL(5)|/FB5$$

Combined pile load factor

$$CBPLF = |FL(3)|/FA + BPLF$$

Maximum pile load factor

$$PLF = \text{Max}(APLF, CBPLF)$$

For each pile the maximum axial and bending pile load factors are defined as

$$APLFMX = \text{Max}_{LC, SC}(APLF)$$

and

$$BPLFMX = \text{Max}_{LC, SC}(BPLF)$$

The objective function FOBJ of the batter slope optimization can now be given as

$$FOBJ = \sum_{I=1}^{\text{Number of Piles}} (WAXIAL * APLFMX(I) + WBEND * BPLFMX(I))$$

where WAXIAL and WBEND are dimensionless weight factors that the designer selects to specify the relative importance of axial and bending loads in the pile. Typically, WAXIAL is taken as 1 and WBEND as 10. Then the optimization search seeks batter slopes which minimize or eliminate bending in the piles. If the overstress factor for a load case is larger than unity, the pile load factors are divided by the overstress factor for the load case.

The evaluation of FOBJ involves the following steps:

1. Place a pile at every grid point in every zone.
2. Assemble the global stiffness matrix for each soil condition.
3. Invert the global stiffness for each soil condition.
4. Repeatedly analyze the pile foundation in a load case loop for each soil condition. Calculate pile cap displacements, pile loads and pile load

factors.

5. Sum up the weighted pile load factors.

The direct search strategy of Nelder and Mead changes the batter slopes ( $H_1, H_2$ ) for each zone so as to minimize the weighted pile load factor sum FOBJ. The Nelder and Mead technique is a method for unconstrained optimization. To cast the batter slope optimization in terms of unconstrained variables, a mathematical transformation is introduced. This transformation is presented in the next section. Following the description of the unconstrained variables transformation is a section that describes the details of the Nelder and Mead direct search strategy.

#### Optimization Variables Transformation

The range on the batter slopes in general is constrained by the inequalities

$$HL_i \leq H_i \leq HU_i \quad i = 1, 2$$

for each zone. Algorithms for constrained optimization generally require much more time than for unconstrained optimization. Consequently, it is convenient to transform from the constrained variables,  $H_i$ , to a set of unconstrained variables,  $y_k$ . The unconstrained variables,  $y_k$ , are introduced by the transformation

$$H_1 = HL_1 + (HU_1 - HL_1) \sin^2(y_1)$$

$$H_2 = HL_2 + (HU_2 - HL_2) \sin^2(y_2)$$

for each zone. The  $y$ -variables can range from  $-\infty$  to  $+\infty$ . Thus if there are NZS zones, there will be  $2 \cdot \text{NZS}$  unconstrained  $y$ -variables. If a particular pile batter slope is to be held constant throughout the optimization, then the limits are set equal and no unconstrained  $y$ -variable is established. The unconstrained  $y$ -variables are purely a numerical convenience and have no physical significance.

### The Nelder and Mead Direct Search Method

The Nelder and Mead direct search method is one of the simplex algorithms of unconstrained numerical optimization (Reference 4). A simplex in the  $n$  dimensional space of the unconstrained  $y$ -variables is defined by a set of  $n+1$  vertices

$$\{y\}_0, \{y\}_1, \{y\}_2, \dots, \{y\}_n$$

The cost function at the  $j$ -th vertex is indicated as  $G_j$ .

To describe the method, suppose that for the  $k$ -th iteration the vertices of the simplex are  $\{y\}_0^k, \{y\}_1^k, \dots, \{y\}_n^k$  with corresponding function values  $G_0, G_1, \dots, G_n$  ordered such that

$$G_n > G_{n-1} > \dots > G_1 > G_0$$

Hence  $\{y\}_0^k$  is the best vertex of the simplex and  $\{y\}_n^k$  is the worst. The objective of the  $k$ -th iteration is to replace the worst vertex by a better one. Let  $\{c\}^k$  be the centroid of the vertices  $\{y\}_0^k, \{y\}_1^k, \dots, \{y\}_{n-1}^k$ , that is

$$\{c\}^k = \frac{1}{n} \sum_{j=1}^{n-1} \{y\}_j^k$$

The first attempt to replace the worst vertex,  $\{y\}_n^k$ , is a reflection move given by

$$\{y\}_r^k = \{c\}^k + \alpha (\{c\}^k - \{y\}_n^k)$$

where  $\alpha > 0$  is the reflection coefficient (usually  $\alpha = 1$ ). There are three possible cases to be considered, that  $\{y\}_r^k$  is a point such that

1.  $G_0 < G_r < G_{n-1}$
2.  $G_r < G_0$
3.  $G_r > G_{n-1}$

The consequences of these three alternatives are

Case 1 -  $\{y\}_r^k$  replaces  $\{y\}_n^k$ .

Case 2 - Since the reflected point  $\{y\}_r^k$  is a new best point, an attempt is made to expand in this direction. The expansion point is given as

$$\{y\}_e^k = \{c\}^k + \beta (\{y\}_r^k - \{c\}^k)$$

where  $\beta > 1$  is the expansion coefficient.

- a. If  $G_e < G_0$ ,  $\{y\}_e^k$  replaces  $\{y\}_n^k$
- b. If  $G_e > G_0$ ,  $\{y\}_r^k$  replaces  $\{y\}_n^k$ .

Case 3 - The reflected point is a new worst point and it is assumed that the simplex is too large. Thus the simplex is contracted by the move

$$\{y\}_c^k = \{c\}^k + \gamma (\{y\}_n^k - \{c\}^k)$$

where  $\gamma$  is a contraction coefficient with  $1 > \gamma > 0$ .

- a. If  $G_c < \min (G_n, G_r)$ ,  $\{y\}_c^k$  replaces  $\{y\}_n^k$
- b. If  $G_c > G_n$ , a more comprehensive contraction move is carried out by halving the distances from the best vertex  $\{y\}_0^k$  of all other vertices of the simplex

$$\{y\}_j^k = (\{y\}_j^k + \{y\}_j^k)/2 \quad . \quad j = 1, \dots, n$$

The reflection, expansion and contraction moves are illustrated in Fig. IV.1.

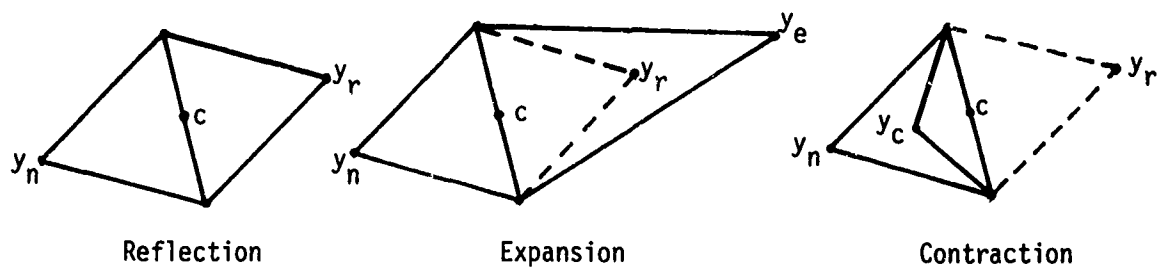


Fig. IV.1 Nelder and Mead Reflection, Expansion and Contraction Moves for a Function of Two Variables

The convergence criterion is based on the variation in the function values over the vertices of the simplex given by

$$\sigma = \sqrt{\sum_{i=0}^n \frac{(G_i - \bar{G})^2}{n}}$$

where  $\bar{G}$  is the mean of the vertex values. When the standard deviation,  $\sigma$ , of the function values falls below some preassigned limit, the search is terminated.

## Phase II - Determination of Pile Spacings and Pile Distribution

To obtain values of the spacings for the grids in the zones, a sequence of one-dimensional searches is performed. This search strategy begins with the spacings set to their minimum values. The program analyzes the pile foundation to determine the pile load factors. In a series of deletion passes, the program removes piles until the best distribution of piles for the given batter slopes and spacings is obtained. The program selects piles to be deleted in two sets of deletion passes. During the first set of deletion passes the least loaded piles (piles with smallest PLF) are deleted on the rationale that they are not being fully utilized. The "least" deletion process continues until no further piles can be deleted without violation of either a load or displacement constraint. Then for the same set of batter slopes and spacings, the deletion process is repeated except the most loaded (piles with largest PLF) are deleted. The idea behind this strategy is that maybe the large loads in the pile are because the pile is misplaced and if it is removed the less loaded piles can pick up its load. Again piles are deleted until further deletion would result in a layout that violates a constraint. The layout obtained from either deleting the least or most loaded piles that is of lower cost (fewer piles) is retained as the best layout for these spacings. The currently active spacing is incremented and the deletion process is repeated. Experience with the typical design problems presented in PART V has indicated that sometimes deleting the least loaded piles leads to a better layout and in other problems deleting the most loaded piles yields a better result. The deletion algorithm is described as follows:

1. The designer selects a maximum number of passes of deletion (ISWMX), a maximum percentage of piles that can be deleted on any pass (PERDLT), and a minimum percentage of piles to delete on a given pass (PDMN).

The program calculates a minimum deletion percentage so that at least

one pile can be deleted from the zone with the largest number of piles. If the minimum deletion percentage is larger than the value of PDMN selected by the user the program replaces PDMN by the larger value.

2. During a deletion pass, the maximum number of piles, MXPd, that can be deleted from a zone is limited to a percentage of the number of piles in the zone, NPLZ, thus

$$MXPd = (PERDLT)(No. of Piles)/100$$

3. A progressive minimum pile load factor, PLFM, is calculated for each deletion pass (ISW) as

$$PLFM = 1 - EXP(-.5*ISW)$$

If  $PLF < PLFM$ , then the pile is deleted, provided the number of piles deleted (NPD) in this manner does not exceed MXPd.

4. If the number of piles, NPD, in a zone that satisfy

$$PLF < PLFM$$

is greater than MXPd, then the piles to be deleted are selected differently. If  $NPD > MXPd$ , the number of compression piles retained, NCPR, is calculated as

$$NCPR = \sum_{\text{Compression Piles}} PLF$$

and the number of tension piles retained, NTPR is given by

$$NTPR = \sum_{\text{Tension Piles}} PLF$$

If  $NCPR + NTPR > NPLZ - MXPd$ , then the NCPR compression piles and NTPR tension piles are retained.

If  $NCPR + NTPR < NPLZ - MXPd$ , then NCPR and NTPR are increased equally so that

$$NCPR + NTPR \geq NPLZ - MXPd$$

With NCPR and NTPR determined, NCPR compression piles with the largest (smallest) PLF and NTPR tension piles with the largest (smallest) PLF are retained. Since the PLFM is progressing toward a value of one as the deletion proceeds, this is the branch in which most of the deletion takes place.

5. If the piles in a zone are all loaded the same, then the piles are retained in a manner so that they are distributed as uniformly as possible over the zone.
6. After the piles to be retained and/or deleted have been determined by steps 3, 4 or 5 for all zones, the pile foundation is reanalyzed for the new distribution as the first step in the next deletion pass. If neither the load nor the displacement constraints are violated, this distribution is accepted as the best yet for the given spacings and further deletion is attempted based upon the above strategy.
7. If a pile in any zone is overloaded or the displacement of any zone corner exceeds the given limits, the distribution is rejected. The distribution is backed up to the last acceptable distribution of piles in the zones. The deletion percentage, PERDLT, is reduced by one-half.

$$\text{PERDLT} = 0.5 * \text{PERDLT}$$

The foundation is reanalyzed, and the deletion is based upon the reduced deletion percentage in the next deletion pass.

8. The deletion passes continue until one of three eventualities terminated either the "least" or the "most" deletion process for the given set of spacings.
  - a. The number of deletion passes, ISW, equals the maximum allowed, ISWMX.
  - b. The deletion percentage, PERDLT, is reduced to less than the minimum value, PDMN. If PDMN is small enough, then this termination occurs

when no more piles can be deleted from the foundation.

c. The number of piles in the foundation does not change on three successive deletion passes.

9. If during the first deletion pass ( $ISW = 1$ ) with piles at all grid points of the zones, a pile is overloaded or a displacement is too large, the deletion process terminates. In this instance, the given spacings are unacceptable. With the maximum number of piles present for these spacings, the foundation still does not satisfy all of the load and displacement constraints.

The above deletion process determines the best distribution of piles in the zones for a given set of spacings and the best batter slopes as calculated in Phase I. The spacings, distributions and pile foundation cost (number of piles) are retained as the best current design.

The spacing,  $SPA_1$ , in the  $U_1$ -direction of Zone 1 is incremented by an amount,  $SINC_1$  (user specified). The deletion process is repeated. If a better result is obtained, that is, if the pile foundation cost for the new design does not exceed the previous cost, these spacings and distribution replace the previous layout as the best foundation design. The spacing being varied is incremented repeatedly until a layout is obtained that has a higher cost or until the spacing reaches its maximum value.

After the best value of  $SPA_1$  of Zone 1 has been determined, then  $SPA_2$  of Zone 1 is incremented to obtain its best value. This sequence of one-dimensional searches is continued through the two spacings of all zones. If the first increment of a new spacing produces a design of higher cost than has previously been obtained, that spacing search is terminated with the particular spacing set to its previous best value. The process is continued by moving on to the next spacing to be searched.

This optimization of the pile foundation design implicitly assumes an independence of the various layout parameters. It is clear that pile layout parameters such as batter slopes, grid spacings and pile distribution are not independent. To perform a more exhaustive search than the sequential process described above would be very demanding in terms of computer run time. A slight variation of the above procedure is available to the user. The variation is the so-called "long" optimization procedure that can be selected by specifying IOASW as 2. In the long optimization, the optimum batter slopes calculation is repeated every time the spacing that is being searched changes. Thus, after the best value of  $SPA_1$  for Zone 1 is obtained, optimum batter slopes are recomputed. Experience has shown in some cases that the new optimum batter slopes are not significantly different from the optimum batter slopes initially calculated.

The optimization of the pile foundation design by this procedure requires considerable computer run time. On large problems (300-500 piles) a large part of the computation time is required in Phase I for the optimum batter slopes calculation. This suggests that the initial spacings used during Phase I should be as large as possible so that the number of piles in the foundation during these analyses is not too large. The user must be careful in using the maximum spacings because he can possibly eliminate all piles that are battered in a given direction in narrow zones.

## PART V: USER'S GUIDE FOR PROGRAM PILEOPT

Documentation of the data input for PILEOPT is presented in this Part. The parameter definitions and order of input are also included.

PILEOPT determines optimum spacings, batter slopes, and distribution of piles in the user-selected zones of the pile cap base. The program analyzes the pile foundation based upon the method of Hrennikoff (Reference 1) as extended by Saul (Reference 2). The soil is represented by a subgrade modulus,  $n_h$ , so that the lateral restraint of the soil varies linearly with depth. The analysis produces the pile cap displacements, the local (or pile) forces, the load factor in each pile, and the global (or foundation) forces.

PILEOPT has some limitations due to setting of certain dimension statements. Two soil conditions can be treated. The number of zones is limited to no more than 15. The maximum number of piles in any zone is 1000, and the total number of piles cannot exceed 2000. There is no specified limit on the number of load cases or on the number of groups of piles. The program runs on the Boeing Computer Service CDC CYBER 175 computer and the Office Personnel Management H 6000 computer.

GROUP I---CONTROL DATA

A. IPR

IPR = PRINT CONTROL PARAMETER BETWEEN 0 AND 99  
0 - FOR MINIMUM OUTPUT (NORMALLY USE 10)

B. HDG

HDG = PROGRAM HEADING (MAX OF 72 CHARACTERS)

C. IPLG,IFL,IFG

IPLG = PILE GEOMETRY  
IFL = LOCAL FORCES  
IFG = GLOBAL FORCES

D. IOASW,NZS,NPGS,NLCS,NSCDS

IOASW = PROGRAM FUNCTION SWITCH  
0 - ANALYSIS  
1 - FOR SHORT OPTIMIZATION  
2 - FOR LONG OPTIMIZATION  
10- FOR SHORT OPTIMIZATION AND TO INPUT CONV  
NZS = NUMBER OF ZONES (MAX 15)  
NPGS = NUMBER OF PILE GROUPS  
NLCS = NUMBER OF LOAD CASES  
NSCDS = NUMBER OF SOIL CONDITIONS

E. NOTE: REPEAT NSCDS NUMBER OF TIMES

SGMNH(ISC),BMF(ISC)

SGMNH(ISC) = SUBGRADE MODULUS FOR ISC-TH SOIL CONDITION  
BMF(ISC) = BENDING MOMENT FACTOR FOR PINNED PILES FOR  
THE ISC-TH SOIL CONDITION

GROUP II---OPTIMIZATION CONTROL DATA

NOTE: NECESSARY ONLY IF IOASW>0

A. ICOST,INEAT,NFMAX

ICOST = COST EVALUATIONS DURING OPTIMIZATION  
 INEAT = ENGINEERING ROUNDING SWITCH  
 RESULTS FOR A FINAL ANALYSIS PASS MAY BE OBTAINED FOR THE  
 VALUE OF BATTER SLOPES CALCULATED BY OPTIMIZATION PROCESS  
 OR FOR ROUNDED VALUES OF BATTER SLOPES USING INCREMENTS  
 GIVEN IN DATA GROUP J  
 0 - RESULTS FOR ONLY COMPUTED VALUES  
 1 - RESULTS FOR ONLY ROUNDED VALUES  
 2 - RESULTS FOR BOTH COMPUTED AND ROUNDED VALUES  
 NFMAX = MAXIMUM NUMBER OF COST FUNCTION EVALUATIONS ALLOWED DURING  
 OPTIMIZATION (ABOUT 300)

B. DAL(1),DAL(2),DAL(3)

DAL = ALLOWABLE DISPLACEMENT OF ANY POINT IN THE PILE CAP  
 IN THE THREE GLOBAL DIRECTIONS

C. WAXIAL,WBEND

WAXIAL = AXIAL PILE LOAD FACTOR  
 WBEND = BENDING PILE LOAD FACTOR

D. ISWMX,PERDLT,PDMN

ISWMX = MAXIMUM NUMBER OF PASSES THROUGH THE DELETION ALGORITHM  
 (ABOUT 6)  
 PERDLT = MAXIMUM PERCENTAGE OF PILES THAT CAN BE DELETED ON ANY  
 DELETION PASS (ABOUT 30)  
 PDMN = MINIMUM PERCENTAGE OF PILES THAT CAN BE DELETED ON ANY  
 DELETION PASS (ABOUT 1)

E. NOTE: NECESSARY ONLY IF IOASW=10

CONV

CONV = CONVERGENCE TOLERANCE

### GROUP III---PHYSICAL PARAMETER DATA

NOTE: REPEAT ENTIRE GROUP NPGS NUMBER OF TIMES

A. IPG,PLCOST(IPG)

IPG = PILE GROUP NUMBER  
PLCOST(IPG) = PER PILE COST OF PILES IN THE IPG-TH PILE GROUP

B. NOTE: NECESSARY ONLY IF PLCOST(IPG)>0

E,AIX,AIY,AREA,PLEN

E = MODULUS OF ELASTICITY  
AIX,AIY = COORDINATES OF AREA MOMENTS OF INERTIA OF PILES IN GROUP  
AREA = AREA OF PILES IN GROUP  
PLEN = LENGTH OF PILES IN GROUP

C. NOTE: NECESSARY ONLY IF PLCOST(IPG)>0

FIX(1),FIX(2),...,FIX(6)

FIX = FIXITY COEFFICIENTS OF THE PILES

D. NOTE: NECESSARY ONLY IF PLCOST(IPG)<=0  
REPEAT NSCDS NUMBER OF TIMES

B(1,IS,IPG),B(2,IS,IPG),...,B(12,IS,IPG)

B(1,IS,IPG),...,B(10,IS,IPG) = LOCAL STIFFNESS COEFFICIENT BIJ OF THE PILE  
B(11,IS,IPG),B(12,IS,IPG) = EFFECTIVE LENGTHS OF THE PILES

E. NOTE: REPEAT NSCDS NUMBER OF TIMES

FA(1,IS,IPG),FA(2,IS,IPG),...,FA(5,IS,IPG)

FA(1,IS,IPG) = ALLOWABLE AXIAL LOAD IN COMBINED AXIAL AND BENDING LOADING  
FA(2,IS,IPG),FA(3,IS,IPG) = ALLOWABLE BENDING MOMENTS ABOUT THE MINOR AND MAJOR PRINCIPAL AXES OF THE PILE, RESPECTIVELY  
FA(4,IS,IPG) = ALLOWABLE COMPRESSIVE LOADS  
FA(5,IS,IPG) = ALLOWABLE TENSION LOADS

GROUP IV---LOAD AND OVERSTRESS FACTOR DATA

NOTE: REPEAT NCLS NUMBER OF TIMES

Q(1,L),Q(2,L),...,Q(7,L)

Q(1,L),...,Q(6,L) = SIX COMPONENTS OF THE APPLIED LOADS REFERRED  
TO THE ORIGIN  
Q(7,L) = OVERSTRESS FACTOR

#### GROUP V---ZONE DATA

NOTE: GROUP V IS NECESSARY ONLY IF NZS>0  
REPEAT GROUP V NZS NUMBER OF TIMES

A. ZTYP(1,IZ),ZTYP(2,IZ),ZTYP(3,IZ)

ZTYP(1,IZ) = TYPE ZONE SWITCH  
1 - FOR RECTANGULAR  
2 - FOR CIRCULAR  
ZTYP(2,IZ) = REPEAT OF ZONE INDICATOR  
0 - FIRST OCCURENCE OF NON-REPEATED ZONE  
>0- INDICATES THAT THIS IS A REPEAT OF THE ZTYP(2,IZ)  
ZONE THAT MUST HAVE BEEN PREVIOUSLY DEFINED  
ZTYP(3,IZ) = FLIP INDICATOR FOR A REPEATED ZONE  
0 - REPEATED ZONE HAS SAME LAYOUT AS PARENT ZONE  
1 - FLIPS THE LAYOUT, BORDERS AND SHEET PILES ABOUT  
AN AXIS PARALLEL TO SIDE OF LENGTH ZLN(1,IZ)  
2 - FLIPS ABOUT 2-AXIS  
3 - FLIPS ABOUT THE 1-AXIS THEN ABOUT THE 2-AXIS  
(CIRCULAR ZONES CAN BE FLIPPED ONLY ABOUT THE 1-AXIS)

B. UZC(1,IZ),UZC(2,IZ),UZC(3,IZ),ALFZN(IZ)

UZC(J,IZ) = J-TH COORDINATE OF THE CORNER OF THE IZ-TH ZONE  
(SPECIFY THE CORNER OF MINIMUM U1 AND U2 BEFORE  
ZONE ROTATION)  
ALFZN(IZ) = ANGLE OF ROTATION OF IZ-TH ZONE FROM THE GLOBAL  
U1 AXIS TOWARD THE GLOBAL U2 AXIS (INITIAL ANGLE  
IN ZONE IS CIRCULAR)

NOTE: INPUT DATA LINES C - G ARE NECESSARY ONLY  
IF ZTYP(2,IZ)=0

C. ZLN(1,IZ),ZLN(2,IZ),ZLN(3,IZ)

ZLN(1,IZ),ZLN(2,IZ) = FIRST AND SECOND DIMENSION OF THE IZ-TH  
ZONE  
ZLN(3,IZ) = THE INITIAL RADIUS IF THE ZONE IS CIRCULAR

D. BOR(1,IZ),BOR(2,IZ),BOR(3,IZ),BOR(4,IZ)

BOR(1,IZ),...,BOR(4,IZ) = WIDTH OF THE BORDER FOR THE SIDES OF  
THE IZ-TH ZONE

E. BOR(5,IZ),BOR(6,IZ),BOR(7,IZ),BOR(8,IZ)

BOR(5,IZ),...,BOR(8,IZ) = SHEET PILE LENGTH FOR THE SIDES OF  
THE IZ-TH ZONE (IF THERE IS NO SHEET  
PILE SET BOR(5,IZ)-BOR(8,IZ) = 0)

F. SPA(1,IZ),SPA(2,IZ),H(1,IZ),H(2,IZ),ALFBT(IZ)

SPA(1,IZ),SPA(2,IZ) = GRID SPACINGS OF THE IZ-TH ZONE

H(1,IZ) = THE BATTER SLOPE OF THE FIRST NPB1  
ROWS (COL.) OF PILES IN THE IZ-TH ZONE

H(2,IZ) = THE BATTER SLOPE FOR THE NEXT NPB2  
ROWS (COL.)

(EITHER OF THESE BATTER SLOPES CAN BE NEGATIVE.

IF THE ALTERNATE GROUPS OF ROWS (COL.) ARE TO  
HAVE OPPOSITE BATTER, THEN THE SIGNS OF H(1,IZ)  
AND H(2,IZ) ARE OPPOSITE)

AFLBT(IZ) = ANGLE CLOCKWISE FROM THE SIDE OF THE ZONE  
THAT IS ZLN(1,IZ) LONG TO THE PLANE OF  
BATTER AND/OR THE MINOR PRINCIPAL AXIS OF  
THE PILE (DEGREES)

G. IPG(IZ),IRC(IZ),NPB1(IZ),NPB2(IZ)

IPG(IZ) = PILE GROUP INDEX

IRC(IZ) = ROW OR COLUMN BATTER SWITCH

1 - IF BATTER CHANGES IN U1 DIRECTION

2 - IF BATTER CHANGES IN U2 DIRECTION

NPB1(IZ) = NUMBER OF ROWS (COL.) IN WHICH BATTER SLOPE IS  
HELD AT H(1,IZ) BEFORE CHANGING TO H(2,IZ)

NPB2(IZ) = NUMBER OF ROWS (COL.) IN WHICH BATTER SLOPE IS  
HELD AT H(2,IZ) BEFORE CHANGING TO H(1,IZ) FOR  
THE NEXT NPB1(IZ) ROWS (COL.)

(THIS PATTERN OF BATTER OF NPB1 THEN NPB2 IS REPEATED  
UNTIL THE BATTER SLOPES OF ALL ROWS (COL.) ARE SPECIFIED)

NOTE: INPUT DATA LINES H - J ARE NECESSARY ONLY  
IF IOASW>0 AND ZTYP(2,IZ)=0

H. SPAL(1,IZ),SPAU(1,IZ),SPAL(2,IZ),SPAU(2,IZ)

SPAL(1,IZ),SPAL(2,IZ) = LOWER LIMITS ON THE SPACING OF THE  
IZ-TH ZONE

SPAU(1,IZ),SPAU(2,IZ) = UPPER LIMITS ON THE SPACING OF THE  
IZ-TH ZONE

I. HL(1,IZ),HU(1,IZ),HL(2,IZ),HU(2,IZ)

HL(1,IZ),HL(2,IZ) = LOWER LIMITS ON THE BATTER SLOPE H(J,IZ)  
HU(1,IZ),HU(2,IZ) = UPPER LIMITS ON THE BATTER SLOPE H(J,IZ)  
(EVEN IF H(J,IZ) IS NEGATIVE THE LIMITS HL AND  
HU SHOULD BE POSITIVE)

J. SINC(1,IZ),SINC(2,IZ),HINC(1,IZ),HINC(2,IZ)

SINC(1,IZ),SINC(2,IZ) = INCREMENTS OF SPACING USED IN THE  
SEARCH FOR OPTIMUM PLACEMENT OF PILES

HINC(1,IZ),HINC(2,IZ) = ACCEPTABLE INCREMENTS IN THE BATTER  
SLOPES DURING THE ROUNDING TO  
ENGINEERING VALUES

K. NPLDLT

NPLDLT = NUMBER OF PILES TO BE DELETED FROM THE GRID POINTS  
OF A ZONE

L. NOTE: REPEAT NLPDLT NUMBER OF TIMES

IDLT,JDLT

IDLT,JDLT = THE I,J INDICIES OF THE PILES TO BE DELETED FROM  
THE ZONE

GROUP VI---PILE GEOMETRIC LAYOUT DATA WHEN NOT IN ZONE FORMAT

A. NPLS

NPLS = NUMBER OF PILES

B. NOTE: REPEAT NPLS NUMBER OF TIMES

$UP(1,IP), UP(2,IP), UP(3,IP), ALF(IP), H(IP), IPG(IP)$
---

$UP(1,IP), \dots, UP(3,IP)$  = IP-TH PILE COORDINATES  
     $ALF(IP)$  = ANGLE TO BATTER  
     $H(IP)$  = BATTER SLOPE  
     $IPG(IP)$  = PILE GROUP INDEX

## PART VI: NUMERICAL RESULTS

In this part the results of several example computer runs of program PILEOPT are presented. The first example is an analysis using PILEOPT of a nine pile foundation that is from Saul (Reference 2). This run establishes the ability of PILEOPT to correctly analyze a pile foundation. The next example is a small design problem that is included because the optimal pile layout is obvious and thus checks the optimization strategy in such pedantic cases. The remaining four examples are realistic pile layout design problems. Included are pile layout designs for a dam sill monolith, a lock gate monolith, an abutment monolith, and a pump station foundation. These problems were furnished by the Structures Section of the St. Louis District of the U.S. Army Corps of Engineers. The example problems are presented by a sketch defining the problem, a table of applied loads, a table of selected zone parameters, a listing of the input data. The results of the problem include a computer generated layout using the graphics postprocessor program at the St. Louis District. A limited listing of the tabular output from PILEOPT completes the results. The example problems were run by John Jobst of the St. Louis District on the Boeing Computer Service CDC CYBER 175 computer system.

### Discussion of Results

Program PILEOPT produced pile layouts for the four realistic foundation design problems considered. For the dam sill monolith, lock gate monolith, abutment monolith and pump station, the layouts obtained by PILEOPT contained fewer piles than the actual designs. The reduction in number of piles ranged from 12 percent for the pump station to 26 percent for the lock gate monolith. The constraints and considerations under which PILEOPT obtained these results are sim-

ilar but not identical to those for the actual designs. These variations of design conditions may account for the differences of the designs obtained by PILEOPT and the actual designs.

These examples establish that PILEOPT can treat realistic pile design problems. The program requires significant computer run time for the larger pile foundations. To obtain the pile layout for a large pile foundation, the program assembles the stiffness matrix and calculates the pile cap displacements and pile loads for hundreds of trial layouts. Each layout contains hundreds of piles. The optimization strategy is heuristic in nature and offers no guarantee that the design obtained will contain the absolute minimum number of piles to support the structure. The strategy does compare a large number of alternate designs and retains the best of those considered. If this program produces satisfactory results, as it appears to do in the cases considered, it may prove to be a valuable aid to pile foundation designers.

#### Extension of Optimization Strategy

The designs obtained may be refined by further developments in the optimization strategy. A possible future development could be to again vary the batter slopes after the current layout is obtained. If a reduction of the weighted pile load factor sum is obtained by varying the batter slopes, then additional pile deletion may be possible for the layout.

#### Discussion of Optimization Control Parameters

The optimization strategy is controlled by several parameters. These include the weight factors WAXIAL and WBEND for the weighted pile load factor sum. The optimum batter slopes are calculated to minimize this pile load factor sum. These factors are multiplied by the sum of the axial pile load factors and the sum of the bending pile load factors respectively so that the importance of axial versus bending pile loading can be controlled by user. In

the examples contained herein the values of 1 and 10 for WAXIAL and WBEND have been used to emphasize the desire to minimize pile bending. A convergence parameter, CONV, to control termination of the optimum batter slope search has a default value of 0.005 in the program. In some cases the search has been made more complete by setting CONV to 0.001. The pile deletion in Phase II of the optimization is controlled by three parameters ISWMX, PERDLT, and PDMN. The maximum number of deletion passes or sweeps for a set of spacings is equal to ISWMX. In all cases run, the number of deletion passes for all sets of spacings has been less than 25, thus a value of 25 is a good setting for this parameter. The more important control parameters for the pile deletion process are the maximum percentage of piles that can be deleted in a pass, PERDLT, and the minimum pile deletion percentage, PDMN. Values between 25 percent and 40 percent have been used for PERDLT. Probably values of 20 to 30 percent are better because if PERDLT is higher too many piles will be deleted in a single pass. If too many piles are deleted, then the program backs up and the deletion percentage is halved. When the deletion percentage falls below the minimum pile deletion percentage, PDMN, the deletion process terminates. Good values of PDMN are limited so that at least one pile can be deleted from a zone. Typically a value of 1 percent is used. If PDMN is less than what is necessary to delete at least one pile from the zone with the maximum number of piles the program overrides the input value by increasing it to the minimum practical value. This is important since PDMN plays an important role in terminating the deletion process. If PDMN is smaller than necessary, the deletion continues until PERDLT has been reduced to less than PDMN and thus needless calculations would be performed without the override feature.

### Example No. 1 - Saul's Nine-Pile Problem

The nine-pile problem from Saul (Reference 2) is presented as the first example of an analysis of a pile foundation using the program PILEOPT. The nine piles are positioned as shown in Fig. VI.1.

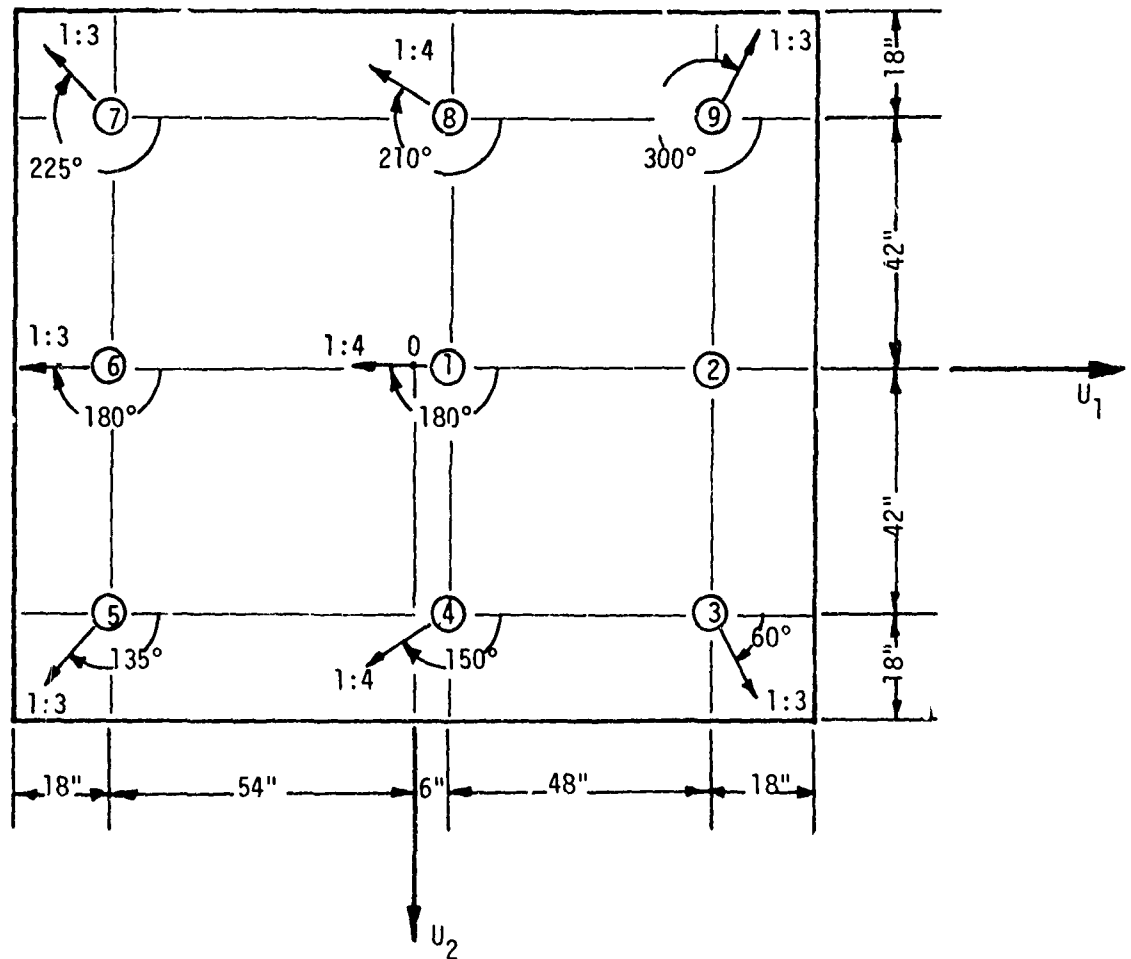


Fig. VI.1 Layout of Saul's Nine-Pile Problem

The properties of the piles are given as

$$E = 3000 \text{ ksi},* \quad I_x = 211.9 \text{ in}^4, \quad I_y = 211.9 \text{ in}^4$$

$$\text{Area} = 16.1 \text{ in}^2, \quad \text{Length} = 1440 \text{ in.}$$

The fixity coefficients are

$$K_1 = 0.567, K_2 = 2.0, K_3 = 1.043, K_4 = 7063, K_5 = K_6 = 0.544.$$

The applied loads are

$$Q_1 = 200 \text{ kips}, \quad Q_2 = 100 \text{ kips}, \quad Q_3 = 1500 \text{ kips}$$

$$Q_4 = 12000 \text{ in-kips}, \quad Q_5 = 48000 \text{ in-kips}, \quad Q_6 = 5000 \text{ in-kips.}$$

The  $U_1, U_2$  coordinates are indicated on Fig. VI.1. From Fig. VI.1 the pile layout data can be tabulated as given in Table VI.1.

Table VI.1 Pile Layout Data for Saul's Problem

Pile No.	$U_1$ -inches	$U_2$ -inches	$U_3$ -inches	ALFBT-degrees	H
1	6	0	0	180	4
2	54	0	0	0	Vertical
3	54	42	0	60	3
4	6	42	0	150	4
5	-54	12	0	135	3
6	-54	0	0	180	3
7	-54	-42	0	225	3
8	6	-42	0	210	4
9	54	-42	0	300	3

\* A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 4.

The input data for program PILEOPT for this problem are given in Table VI.2.

Table VI.2 Input Data for Saul's Problem

```

0
  ANALYSIS EXAMPLE NO.1 - 9 PILE PROBLEM FROM SAUL
1,1,1
0,0,1,1,1
  1,0 722
1,100
30000,211 9,711 9,16.1,1440
  567,2,1.043,7063.3,.544,.544
300,850,850,300,60
200,100,1500,12000,48000,5000,1
9
6,0,0,180,4,1
54,0,0,0,150,1
54,42,0,60,3,1
6,42,0,150,4,1
-54,42,0,135,3,1
-54,0,0,180,3,1
-54,-42,0,225,3,1
6,-42,0,210,4,1
54,-42,0,300,3,1

```

The output from program PILEOPT for this problem is given in Table VI.3.  
Comparing the stiffness matrix, pile cap displacements, and local forces in the piles to the values in Reference 2 shows that PILEOPT obtained identical results.

Table VI.3 Output from PILEOPT for Analysis Example 1

```

***** PROGRAM PILEOPT *****

ANALYSIS AND OPTIMAL DESIGN OF PILE
FOUNDATIONS FOR CONCRETE MONOLITHS

PROBLEM HEADING:

ANALYSIS EXAMPLE NO.1 - 9 PILE PROBLEM FROM SAUL

PRINT LEVEL = 0 (BETWEEN 0 AND 99, MORE AND MORE
                  INTERMEDIATE RESULTS ARE PRINTED.)

```

(Continued)

Table VI.3 (Continued)

PROGRAM FUNCTION SELECTION = 0  
(0 FOR ANALYSIS, GT 0 FOR  
OPTIMAL DESIGN)

NUMBER OF ZONES = 0  
NUMBER OF PILE GROUPS = 1  
NUMBER OF LOAD CASES = 1  
  
NUMBER OF SOIL COND. = 1

SOIL CONDITION NO. = 1  
SUBGRADE MODULUS = .10000E+00  
BENDING MOMENT FACTOR = .72200E+00

OUTPUT CONTROL OPTIONS:  
(TABLE ? 0-NO, 1-YES)  
IPLG = 1(PILE GEOMETRY)  
IFL = 1(LOCAL FORCES)  
IFG = 1(GLOBAL FORCES)

\*\*\*\*\* PILE GROUP DATA \*\*\*\*\*

GROUP NO. 1 PILE COST = 100.00  
F = .300E+05 IX = 211.9000 IY = 211.9000  
AREA = 16.1000 LENGTH = 1440.0000  
K1 = .567 K2 = 2.000 K3 = 1.043  
K4 = 7063.300 K5 = .544 K6 = .544

SOIL CONDITION NO. = 1 NH = 10000E+00  
LOCAL STIFFNESS MATRIX B

.750E+02	0.	0.	0.	.262E+04	0.
0	.750E+02	0.	-.262E+04	0	0
0.	0.	.671E+03	0.	0.	0
0.	-.262E+04	0	.182E+06	0.	0.
.262E+04	0	0.	0.	.182E+06	0.
0.	0	0.	0.	0	.706E+04

ALLOWABLE FORCES AND BENDING MOMENTS  
FA = 300.0 FB4 = 850.0 FB5 = 850.0  
CALOW = 300.0 TALOW = 60.0

(Continued)

Table VI.3 (Continued)

LOAD CASE	TABLE OF APPLIED LOADS			OVERSTRESS FACTOR
	Q1 M1	Q2 M2	Q3 M3	
1	.70000E+03 12000E+05	.10000E+03 .48000E+05	.15000E+04 .50000E+04	1.000

TABLE OF NON-ZONE PILE LAYOUT DATA

PILE NO	PILE COORDINATES			ANGLE TO BATTER	BATTER FROM SLOPE	FROM GROUP
	U1	U2	U3			
1	6.00	0.00	0.00	180.00	4.00	1
2	54.00	0.00	0.00	0.00	150.00	1
3	54.00	42.00	0.00	60.00	3.00	1
4	6.00	42.00	0.00	150.00	4.00	1
5	-54.00	42.00	0.00	135.00	3.00	1
6	-54.00	0.00	0.00	180.00	3.00	1
7	-54.00	-42.00	0.00	225.00	3.00	1
8	6.00	-42.00	0.00	210.00	4.00	1
9	54.00	-42.00	0.00	300.00	3.00	1

## SOIL CONDITION NO. 1

## STIFFNESS MATRIX S

.9113E+03	-.3180E-04	-.6358E+03	.1339E-01	.8025E+04	.2872E-02
-.3180E-04	.8412E+03	.2884E-03	.6876E+04	.1391E-01	.1771E+04
-.6358E+03	.2884E-03	.5634E+04	.1317E-02	-.1176E+05	-.2729E-01
.1339E-01	.6876E+04	.1317E-02	.8395E+07	.1214E-01	.8573E+06
-.8025E+04	.1391E-01	-.1176E+05	.1214E-01	.1281E+08	-.3510E+00
.2872E-02	.1771E+04	-.2729E-01	.8573E+06	-.3510E+00	.3048E+07

## FLEXIBILITY MATRIX F

.1201E-02	-.1370E-11	.1374E-03	-.2014E-11	.8782E-06	.7666E-12
-.1370E-11	.1197E-02	-.6618E-10	-.9361E-06	-.1372E-11	-.4324E-06
.1374E-03	-.6618E-10	.1935E-03	-.3769E-12	.2636E-06	.1778E-11
-.2014E-11	-.9361E-06	-.3769E-12	.1233E-06	-.1643E-14	-.3414E-07
.8782E-06	-.1372E-11	.2636E-06	-.1643E-14	.7884E-07	.1187E-13
.7666E-12	-.4324E-06	.1778E-11	-.3414E-07	.1187E-13	.3380E-06

## RESULTS FOR SOIL CONDITION NO. 1

LOAD CASE	PILE CAP DISPLACEMENTS					
	U1	U2	U3	U4	U5	U6
1	.488E+00	106E+00	.330E+00	.127E-02	.436E-02	.124E-02

(Continued)

Table VI.3 (Concluded)

PILE NO.	LOAD CASE	PILE FORCES ALONG PILE AXES			PILE LOAD FACTOR
		F1 M1	F2 M2	F3 M3	
1	1	-.52443E+02	- 46599E+01	.11858E+03	3.047
		.27833E+02	-.22763E+04	.63935E+01	
2	1	.48003E+02	.98005E+01	.63888E+02	2.922
		-.23120E+03	.20714E+04	.87365E+01	
3	1	.25657E+02	-.31688E+02	.17119E+03	3.448
		.14484E+04	.99761E+03	.18070E+02	
4	1	-.41267E+02	-.25815E+02	.17902E+03	3.900
		.97270E+03	-.18386E+04	.10403E+02	
5	1	- 44880E+02	- 29717E+02	.33291E+03	4.227
		.11930E+04	-.19246E+04	.13247E+02	
6	1	-.59533E+02	.10740E+01	.25636E+03	3.974
		-.17813E+03	-.24737E+04	.55735E+01	
7	1	-.47167E+02	.37343E+02	.24049E+03	4.951
		-.16788E+04	-.18478E+04	-.51019E+00	
8	1	-.51049E+02	.21848E+02	.79427E+02	3.964
		-.10750E+04	-.20692E+04	.29420E+01	
9	1	.15951E+02	.50443E+02	.53626E+02	3.614
		-.20689E+04	.85075E+03	.12708E+01	

PILE FOUNDATION COST = 900.00

LOAD CASE	PILE NO.	PILE FORCES ALONG GLOBAL AXES		
		F1 M1	F2 M2	F3 M3
1	1	.22118E+02	.46599E+01	.12776E+03
		-.28552E+02	.22763E+04	-.54795E+00
1	2	.48003E+02	.98005E+01	.63888E+02
		-.23120E+03	.20714E+04	.87365E+01
1	3	.66681E+02	.52118E+02	.15429E+03
		-.17408E+03	.16937E+04	-.44087E+03
1	4	.99771E+01	.24048E+02	.18368E+03
		.99894E+02	.20654E+04	-.22582E+03
1	5	-.23322E+02	.65348E+02	.33002E+03
		.55764E+03	.21641E+04	-.36469E+03
1	6	-.24589E+02	.10740E+01	.26203E+03
		.16723E+03	.24737E+04	.61618E+02
1	7	.42706E+01	-.48540E+02	.24307E+03
		-.18027E+03	.24329E+04	.53041E+03
1	8	.37131E+02	-.37905E+01	.89437E+02
		-.13202E+03	.23131E+04	.26359E+03
1	9	.59731E+02	-.25697E+01	.45830E+02
		-.24440E+03	.21248E+04	.65540E+03

ARRAY A(NMAX) CONTAINED 111 WORDS.

### Example No. 2 - Small Pile Foundation

A small design problem is presented in this example to illustrate the use of the program PILEOPT. In this problem a square foundation 100 inches by 100 inches is loaded by a 1500 kip vertical force and a 500 kip horizontal force applied at the center. The piles used in the foundation are identical to those in Saul's problem in the previous example. The optimum batter slope is clearly 3:1. Since the axial load carrying capacity of each pile is 300 kip, it will require six piles to support the foundation. A sketch of the foundation is given below in Fig. VI.2.

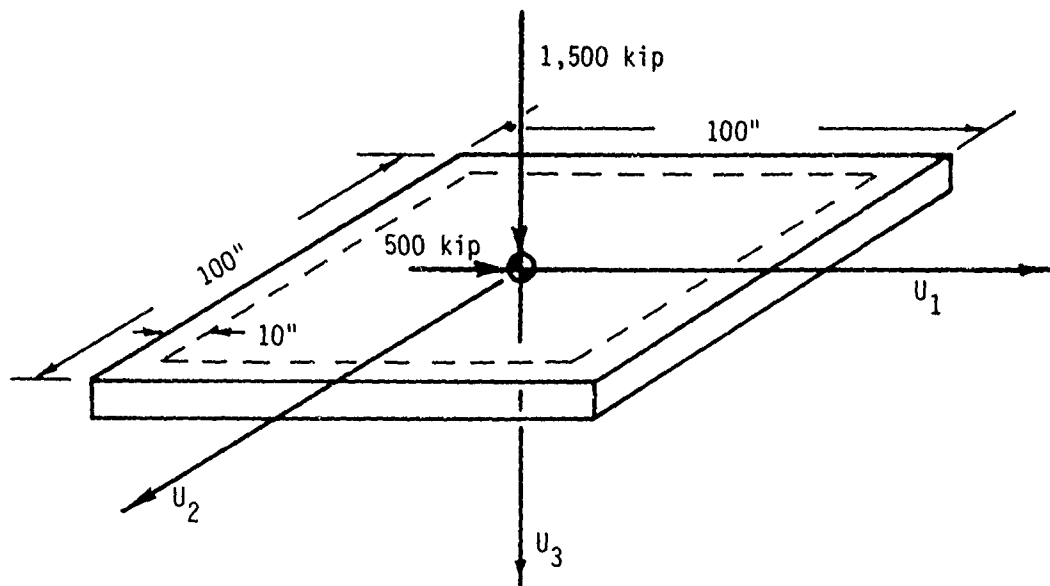


Fig. VI.2 Small Pile Foundation

The pile foundation is considered a single zone. The zone lengths are 100 inches with borders of 10 inches. The piles are allowed to be battered in the  $U_1$ -direction with a slope between 2 and 100. The piles are embedded in the pile cap. The input data for this problem are given in Table VI.4.

Table VI.4 Input Data for Small Optimization Problem

```

10
      SMALL OPTIMIZATION EXAMPLE
1, 1, 0
1, 1, 1, 1, 1
0.1, 0.772
1, 2, 100
1.0, 1.0, 1.0
1, 10
40, 30., 1.
1, 100.0
3E4, 211.9, 211.9, 16.1, 1440.0
0.567, 2.0, 1.043, 7063.3, 0.544, 0.544
300, 500, 500, 300, 60
500, 0, 1500, 0, 0, 0, 1
1, 0, 0
-50, -50, 0, 0
100, 100, 0
10, 10, 10, 10
0, 0, 0, 0
24, 24, 2, 150, 0,
1, 1, 1, 0
24, 42, 24, 42
2, 150, 150, 150
6.0, 6.0, 0.5, 0.5

```

Program PILEOPT obtained the expected pile layout of six piles battered in the  $U_1$ -direction with  $H = 3.00$ . The layout is given in Fig. VI.3. The output from program PILEOPT is given in Table VI.5.

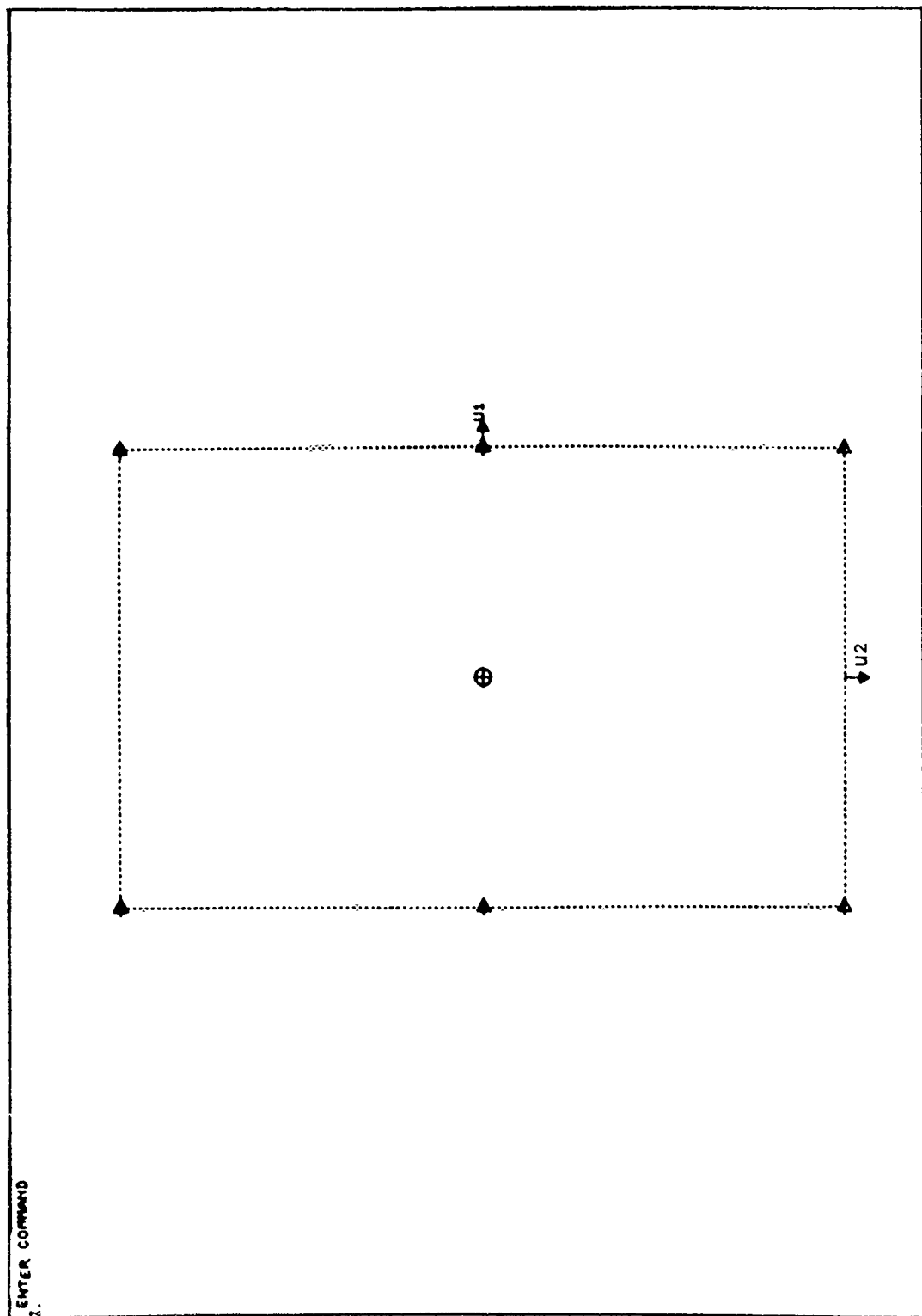


Fig. VI.3 Pile Layout for Small Foundation

Table VI.5 Output from PILEOPT for Small Optimization Example

```
***** PROGRAM PILEOPT *****

ANALYSIS AND OPTIMAL DESIGN OF PILE
FOUNDATIONS FOR CONCRETE MONOLITHS

PROBLEM HEADING:

SMALL OPTIMIZATION EXAMPLE

PRINT LEVEL = 10 (BETWEEN 0 AND 99, MORE AND MORE
                    INTERMEDIATE RESULTS ARE PRINTED.)

PROGRAM FUNCTION SELECTION = 1
(O FOR ANALYSIS, GT 0 FOR
OPTIMAL DESIGN)

NUMBER OF ZONES      = 1
NUMBER OF PILE GROUPS = 1
NUMBER OF LOAD CASES = 1

NUMBER OF SOIL COND. = 1

SOIL CONDITION NO. = 1
SUBGRADE MODULUS = .10000E+00
BENDING MOMENT FACTOR = .77200E+00

OUTPUT CONTROL OPTIONS:
(TABLE ? 0-NO, 1-YES)
IPLG = 1(PILE GEOMETRY)
IFL = 1(LOCAL FORCES)
IFG = 0(GLOBAL FORCES)
ICOST = 1(COST EVALUATIONS)
INEAT = 2(ENGINEERING ROUNDING)
NFMAX = 100(MAX NO. OF COST EVALUATIONS)

ALLOWABLE DISPLACEMENT.
D1 = .1000E+01 D2 = 1000E+01 D3 = 1000E+01

WEIGHT FACTORS FOR OPTIMIZATION
AXIAL PILE LOAD FACTOR = 1.00
```

(Continued)

Table VI.5 (Continued)

BENDING PILE LOAD FACTOR = 10.00

PILE DELETION CONTROL PARAMETERS

MAXIMUM NUMBER OF DELETION PASSES = 40  
 MAXIMUM PERCENT DELETE = 30.000  
 MINIMUM PERCENT DELETE = 1.000

\*\*\*\*\* PILE GROUP DATA \*\*\*\*\*

GROUP NO. 1 PILE COST = 100.00  
 E = .300E+05 IX = 211.9000 IY = 211.9000  
 AREA = 16.1000 LENGTH = 1440.0000  
 K1 = .567 K2 = 2.000 K3 = 1.043  
 K4 = 7063.300 K5 = .544 K6 = .544

SOIL CONDITION NO. = 1 NH = .10000E+00

LOCAL STIFFNESS MATRIX B

.750E+02	0.	0.	0.	.762E+04	0.
0.	750E+02	0.	-.262E+04	0.	0.
0.	0.	.671E+03	0.	0.	0.
0.	-.262E+04	0.	182E+06	0.	0.
.262E+04	0.	0.	0.	.182E+06	0.
0.	0.	0.	0.	0.	.706E+04

ALLOWABLE FORCES AND BENDING MOMENTS

FA = 300.0 FB4 = 500.0 FB5 = 500.0  
 CALOW = 300.0 TALOW = 60.0

TABLE OF APPLIED LOADS

LOAD CASE	Q1 M1	Q2 M2	Q3 M3	OVERSTRESS FACTOR
1	.50000E+03	0.	.15000E+04	1.000
	0.	0.	0.	

\*\*\*\*\* PILE ZONE DATA \*\*\*\*\*

ZONE NO.	TYPE	REPEAT OF ZONE	FLIP AXIS
1	1	0	0

(Continued)

Table VI.5 (Continued)

ZONE	ZONE CORNER COORDINATES			INITIAL	ROTATION
NO.	Uzc-1	Uzc-2	Uzc-3	RADIUS	ALPHA-Z
1	-50.00	-50.00	0.00	0.00	0.00

ZONE	ZONE DIMENSIONS		ZONE BORDERS			
NO.	LENGTH-1	LENGTH-2	BOR-1	BOR-2	BOR-3	BOR-4
1	100.00	100.00	10.00	10.00	10.00	10.00

ZONE	SHEET PILE LENGTHS			
NO.	SPL-1	SPL-2	SPL-3	SPL-4
1	0.00	0.00	0.00	0.00

ZONE	INITIAL GRID SPACINGS		INITIAL BATTER SLOPES	
NO.	SPA-1	SPA-2	H-1	H-2
1	24.00	24.00	2.00	150.00

ZONE	BATTER PATTERN PARAMETERS			
NO.	DIR. OF CHANGE	PATTERN NUMBERS N1,N2	ANGLE TO BATTER	PILE GROUP
1	1	1, 0	0.00	1

TABLES OF LIMITING VALUES  
(USED FOR OPTIMIZATION)

ZONE	SPA-1 MIN	SPA-1 MAX	SPA-2 MIN	SPA-2 MAX
1	24.00	42.00	24.00	42.00

ZONE	H-1 MIN	H-1 MAX	H-2 MIN	H-2 MAX
1	2.00	150.00	150.00	150.00

ZONE	SPA-1 INC	SPA-2 INC	H-1 INC	H-2 INC
1	6.00	6.00	.50	.50

SUMMARY OF ZONE RECTANGULAR GRIDS  
USED IN THE OPTIMIZATION

ZONE	MAX NO.	MAX NO.	MAX NO.
------	---------	---------	---------

(Continued)

Table VI.5 (Continued)

NO. OF ROWS OF COLS OF FILES

1 4 4 16

MAX NO. OF FILES IN FOUNDATION = 16

MIN. PERCENT DELETE HAS BEEN INCREASED PIMN = 6.150

NUMBER OF OPTIMIZATION VARIABLES = 1

INITIAL SPACINGS ARE USED FOR  
OPTIMUM BATTER SLOPES CALCULATION

SPACINGS FOR THIS OPTIMIZATION PASS

ZONE	SPA-1	SPA-2
1	.24000E+02	.24000E+02

NF	AXIAL PLF	BENDING PLF	WEIGHTED PLF	NUMBER OF PILES IN ZONE 1
0	.52175E+01	.12691E+02	.13213E+03	16
1	.50000E+01	.29351E+02	.29851E+03	16
2	.50000E+01	.29351E+02	.29851E+03	16
3	.50000E+01	.29351E+02	.29851E+03	16
4	.50000E+01	.29351E+02	.29851E+03	16
5	.50000E+01	.29351E+02	.29851E+03	16
6	.50443E+01	.26893E+02	.27398E+03	16
7	.50443E+01	.26893E+02	.27398E+03	16
8	.51298E+01	.21278E+02	.21791E+03	16
9	.51298E+01	.21278E+02	.21791E+03	16
10	.52476E+01	.85803E+01	.91051E+02	16
11	.51298E+01	.21278E+02	.21791E+03	16
12	.52643E+01	.43953E+01	.49218E+02	16
13	.52175E+01	.12691E+02	.13213E+03	16
14	.52685E+01	.24980E+01	.30248E+02	16
15	.52476E+01	.85803E+01	.91051E+02	16
16	.52702E+01	.92689E+00	.14539E+02	16
17	.52643E+01	.43953E+01	.49218E+02	16
18	.52703E+01	.80453E+00	.13316E+02	16
19	.52685E+01	.24980E+01	.30248E+02	16
20	.52705E+01	.57884E-01	.58493E+01	16
21	.52702E+01	.92689E+00	.14539E+02	16
22	.52704E+01	.37434E+00	.90138E+01	16
23	.52704E+01	.49176E+00	.10188E+02	16
24	.52705E+01	.15846E+00	.68551E+01	16
25	.52704E+01	.27464E+00	.80169E+01	16
26	.52705E+01	.50343E-01	.57739E+01	16
27	.52705E+01	.15846E+00	.68551E+01	16

(Continued)

Table VI.5 (Continued)

28	.52705E+01	.37575E-02	.53080E+01	16
29	.52705E+01	.57884E-01	.58493E+01	16
30	.52705E+01	.23296E-01	.55034E+01	16
31	.52705E+01	.30818E-01	.55786E+01	16
32	.52705E+01	.97701E-02	.53682E+01	16
33	.52705E+01	.17287E-01	.54433E+01	16
34	.52705E+01	.30065E-02	.53005E+01	16

MINIMUM WTD PLF SUM = .53005E+01

## OPTIMUM BATTER SLOPES

ZONE	H-1 OPT	H-2 OPT
1	.30003E+01	.15000E+03

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.24000E+02	.24000E+02

## DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	4	4	16	.330	1
1	4	4	12	.582	2
1	4	4	9	1.303	3
1	4	4	12	.582	4
1	4	4	11	.664	5
1	4	4	10	.856	6
1	4	4	9	.695	7
1	4	4	8	1.016	8
1	4	4	9	.695	9
1	4	4	9	.695	10
1	4	4	9	.695	11
1	4	4	9	.695	40

NO. OF PILES = 9

EXCESS PLF = 0.

MAX. DISPL. = .7783E-01 .1535E-01 .2817E+00

PFCOST = 900.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .248

## DELETING THE MOST LOADED PILES

(Continued)

Table VI.5 (Continued)

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	4	4	16	.330	1
1	4	4	12	.582	2
1	4	4	9	2.705	3
1	4	4	12	.582	4
1	4	4	11	1.055	5
1	4	4	12	.582	6
1	4	4	12	.582	7
1	4	4	12	.582	8
1	4	4	12	.582	9
1	4	4	12	.582	40

NO. OF PILES = 12

EXCESS PLF = 0.

MAX. DISPL. = .3626E-01 .9923E-15 .2372E+00

PFCOST = 1200.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .215

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.30000E+02	.24000E+02

## DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	3	4	12	.439	1
1	3	4	9	.818	2
1	3	4	9	.818	3
1	3	4	8	.927	4
1	3	4	8	.927	5
1	3	4	8	.927	6
1	3	4	8	.927	7
1	3	4	8	.927	8
1	3	4	8	.927	9
1	3	4	8	.927	40

NO. OF PILES = 8

EXCESS PLF = 0.

MAX. DISPL. = 5109E-01 .6741E-02 .3722E+00

PFCOST = 800.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .207

(Continued)

Table VI.5 (Continued)

## DELETING THE MOST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	3	4	12	.439	1
1	3	4	9	.818	2
1	3	4	9	.818	3
1	3	4	8	1.713	4
1	3	4	9	.818	5
1	3	4	8	1.713	6
1	3	4	9	.818	7
1	3	4	9	.818	8
1	3	4	9	.818	9
1	3	4	9	.818	40

NO. OF PILES = 9

EXCESS PLF = 0.

MAX. DISPL. = .9363E-01 .5016E-01 .3105E+00

PFCOST = 900.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .175

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.36000E+02	.24000E+02

## DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	3	4	12	.439	1
1	3	4	9	.823	2
1	3	4	9	.823	3
1	3	4	8	.900	4
1	3	4	8	.900	5
1	3	4	8	.900	6
1	3	4	8	.900	7
1	3	4	8	.900	8
1	3	4	8	.900	9
1	3	4	8	.900	40

NO. OF PILES = 8

EXCESS PLF = 0.

MAX. DISPL. = .5624E-01 7085E-02 .3635E+00

PFCOST = 800.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = 206

(Continued)

Table VI.5 (Continued)

DELETING THE MOST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	3	4	12	.439	1
1	3	4	9	.823	2
1	3	4	9	.823	3
1	3	4	8	1.673	4
1	3	4	9	.823	5
1	3	4	8	1.673	6
1	3	4	9	.823	7
1	3	4	9	.823	8
1	3	4	9	.823	9
1	3	4	9	.823	40

NO. OF PILES = 9

EXCESS PLF = 0.

MAX. DISPL. = .9182E-01 .4845E-01 .3110E+00

PFCOST = 900.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .172

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.42000E+02	24000E+02

DELETING THE LEAST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	4	8	.659	1
1	2	4	8	.659	2
1	2	4	8	.659	3
1	2	4	4	17.068	4
1	2	4	8	.659	5
1	2	4	4	17.068	6
1	2	4	8	.659	7
1	2	4	4	17.068	8

SWEEP = 8 FAILED BACK-UP TO SWEEP = 7

DELETION TERMINATED: PERMIT TO PUMP.

NO. OF PILES = 8

EXCESS PLF = 0.

MAX. DISPL. = .2675E+01 .3106E-13 .7650E+01

PFCOST = 800.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .066

(Continued)

Table VI.5 (Continued)

DELETING THE MOST LOADED PILES

\*\*\*\*\* FILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	4	8	.659	1
1	2	4	8	.659	2
1	2	4	8	.659	3
1	2	4	4	17.068	4
1	2	4	8	.659	5
1	2	4	4	17.068	6
1	2	4	8	.659	7
1	2	4	4	17.068	8

SWEEP = 8 FAILED BACK-UP TO SWEEP = 7

DELETION TERMINATED: PERDIT ) POMN.

NO. OF PILES = 8

EXCESS PLF = 0.

MAX. DISPL. = .2675E+01 .3106E-13 .7650E+01

PFCOST = 800.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .067

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.42000E+02	.30000E+02

DELETING THE LEAST LOADED PILES

\*\*\*\*\* FILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	3	6	.879	1
1	2	3	6	.879	2
1	2	3	6	.879	3
1	2	3	6	.879	4
1	2	3	6	.879	5
1	2	3	6	.879	6
1	2	3	6	.879	7
1	2	3	6	.879	8
1	2	3	6	.879	9
1	2	3	6	.879	10

NO. OF PILES = 6

EXCESS PLF = 0.

MAX. DISPL. = .1243E+00 0. .3727E+00

PFCOST = 600.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

(Continued)

Table VI.5 (Continued)

TIME REQUIRED FOR THIS DELETION = .040

# DELETING THE MOST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	3	6	.879	1
1	2	3	6	.879	2
1	2	3	6	.879	3
1	2	3	6	.879	4
1	2	3	6	.879	5
1	2	3	6	.879	6
1	2	3	6	.879	7
1	2	3	6	.879	8
1	2	3	6	.879	9
1	2	3	6	.879	40

NO. OF PILES = 6

EXCESS PLF = 0.

MAX. DISPL. = .1743E+00 0. .3727E+00

PFCOST = 600.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .039

# SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.42000E+02	.36000E+02

# DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	3	6	.879	1
1	2	3	6	.879	2
1	2	3	6	.879	3
1	2	3	6	.879	4
1	2	3	6	.879	5
1	2	3	6	.879	6
1	2	3	6	.879	7
1	2	3	6	.879	8
1	2	3	6	.879	9
1	2	3	6	.879	40

NO. OF PILES = 6

EXCESS PLF = 0

MAX. DISPL. = 1243E+00 0 3727E+00

PFCOST = 600.00

(Continued)

Table VI.5 (Continued)

OBTAINED BY DELETING THE LEAST LOADED PILES.  
TIME REQUIRED FOR THIS DELETION = .040

DELETING THE MOST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	3	6	.879	1
1	2	3	6	.879	2
1	2	3	6	.879	3
1	2	3	6	.879	4
1	2	3	6	.879	5
1	2	3	6	.879	6
1	2	3	6	.879	7
1	2	3	6	.879	8
1	2	3	6	.879	9
1	2	3	6	.879	40

NO. OF PILES = 6

EXCESS PLF = 0.

MAX. DISPL. = .1243E+00 0. 3727E+00

PFCOST = 600.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = .038

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.42000E+02	.42000E+02

DELETING THE LEAST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	2	4	1.318	1

SPACING IS UNACCEPTABLE. WITH PILES AT

ALL POSSIBLE GRID POINTS, SOME PILES ARE OVERLOADED

EXCESS PLF = .12732E+01 PFCOST = .10000E+08

TIME REQUIRED FOR THIS DELETION = .012

DELETING THE MOST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

(Continued)

Table VI.5 (Continued)

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	2	2	4	1 318	1

SPACING IS UNACCEPTABLE. WITH PILES AT  
 ALL POSSIBLE GRID POINTS, SOME PILES ARE OVERLOADED  
 EXCESS PLF = .12732E+01 PFCOST = .10000E+08  
 TIME REQUIRED FOR THIS DELETION = .013

## CPU TIME

OPTIMUM BATTER SLOPE PHASE	.958 SECONDS
PILE DELETION PHASE	1.558 SECONDS

\*\*\*\*\* OPTIMIZATION RESULTS \*\*\*\*\*

OPTIMUM PILE FOUNDATION COST = 600.00

ZONE NO	OPTIMUM SPACINGS		OPTIMUM BATTER SLOPES	
	SPA-1	SPA-2	H-1	H-2
1	.12000E+02	.36000E+02	.30003E+01	15000E+03

## PLACEMENT OF PILES IN ZONES

ZONE 1 HAS 2 ROWS, 3 COLS, 6 PILES WITH 0 DELETED

TOTAL NUMBER OF PILES = 6

SOIL CONDITION NO 1  
 STIFFNESS MATRIX S

8073E+03 0	1072E+04 0	1489E+05 0
0 4498E+03 0	- 1489E+05 0	4962E+04
1072E+04 0	3668E+04 0	- 4962E+04 0
0 - 1489E+05 0	4158E+07 0	- 1242E+07
1489E+05 0	4962E+04 0	2711E+07 0

(Continued)

Table VI.5 (Continued)

0.	.4962E+04 0.	-.1242E+07 0.	.1043E+07
FLEXIBILITY MATRIX F			
.2532E-02 0	-.7611E-03 0.	- .1529E-04 0	
0.	2525E-02 0	.8463E-05 0	- .1932E-05
- .7611E-03 0.	5021E-03 0.	5098E-05 0.	
0.	.8463E-05 0.	4016E-06 0.	.4379E-06
- .1529E-04 0.	.5098E-05 0.	.4621E-06 0.	
0.	- .1932E-05 0.	.4379E-06 0.	.1489E-05

## RESULTS FOR SOIL CONDITION NO. 1

LOAD	PILE CAP DISPLACEMENTS						
CASE	D1	D2	D3	D4	D5	D6	DMAX
1	.124E+00 0.		.373E+00 0		-.838E-06 0.		.393E+00

***** PILE GEOMETRIC LAYOUT *****									
ZONE	GRID	PT.	PILE	COORDINATES			ANGLE TO BATTER		PILE
NO.	I	J	NO.	U1	U2	U3	BATTER	SLOPE-H	GROUP
1	1	1	1	-21.00	-36.00	0.00	0.00	3.00	1
	1	2	2	-21.00	0.00	0.00	0.00	3.00	1
	1	3	3	-21.00	36.00	0.00	0.00	3.00	1
	2	1	4	21.00	-36.00	0.00	0.00	3.00	1
	2	2	5	21.00	0.00	0.00	0.00	3.00	1
	2	3	6	21.00	36.00	0.00	0.00	3.00	1

## RESULTS FOR SOIL CONDITION NO. 1

				PILE FORCES ALONG PILE AXES			PILE LOAD FACTORS	
ZONE	GRID	PT.	LOAD	F1	F2	F3	AXIAL	COMBINED
NO.	I	J	CASE	M1	M2	M3	BENDING	MAXIMUM
1	1	1	1	.90854E-02 0.		.26351E+03	.878	.879
				0.	.24058E+00 0.		.000	.879
1	1	2	1	.90854E-02 0.		.26351E+03	.878	.879
				0.	.24058E+00 0.		.000	.879
1	1	3	1	.90854E-02 0.		.26351E+03	.878	.879
				0.	.24058E+00 0		.000	.879
1	2	1	1	.82506E-02 0		.26353E+03	.878	.879
				0	.21146E+00 0.		.000	.879
1	2	2	1	.82506E-02 0		.26353E+03	.878	.879
				0.	.21146E+00 0		.000	.879

(Continued)

Table VI.5 (Continued)

1	2	3	1	.82506E-02 0.	.26353E+03	.878	.879
			0.	.21146E+00 0.		.000	.879

FOR SOIL CONDITION NO. 1 SUM OF PLF = .52732E+01

PILE FOUNDATION COST = 600.00

\*\*\*\*\* ENGINEERING ROUNDING \*\*\*\*\*

ZONE SPACINGS AND BATTER SLOPES HAVE  
BEEN ROUNDED TO THE SPECIFIED INCREMENTS

ZONE NO	ROUNDED SPACINGS		ROUNDED BATTER SLOPES	
	SPA-1	SPA-2	H-1	H-2
1	.42000E+02	.36000E+02	.30000E+01	.15000E+03

PLACEMENT OF PILES IN ZONES

ZONE 1 HAS 2 ROWS, 3 COLS, 6 PILES WITH 0 DELETED.

TOTAL NUMBER OF PILES = 6

SOIL CONDITION NO. 1

STIFFNESS MATRIX S

.8073E+03 0.	.1073E+04 0.	.1489E+05 0.
0.	.4498E+03 0.	- .1489E+05 0.
.1073E+04 0.	3667E+04 0.	- .4963E+04 0.
0.	- .1489E+05 0.	.4158E+07 0.
.1489E+05 0.	- 4963E+04 0.	.2711E+07 0.
0.	.4963E+04 0.	- .1242E+07 0.
		.1043E+07

FLEXIBILITY MATRIX F

.2532E-02 0.	- 7611E-03 0.	- .1529E-04 0.
--------------	---------------	----------------

(Continued)

Table VI.5 (Continued)

0.	.2525E-02	0.	.8463E-05	0.	-.1932E-05
-.7611E-03	0.	.5022E-03	0.	.5098E-05	0.
0.	.8463E-05	0.	.4017E-06	0.	.4379E-06
-.1529E-04	0.	.5098E-05	0.	.4621E-06	0.
0.	-.1932E-05	0.	.4379E-06	0.	.1489E-05

## RESULTS FOR SOIL CONDITION NO. 1

LOAD CASE	D1	D2	PILE CAP DISPLACEMENTS				D6	DMAX
			D3	D4	D5			
1	.124E+00	0.	.373E+00	0.	-.278E-16	0.	393E+00	

***** PILE GEOMETRIC LAYOUT *****									
ZONE NO.	GRID I	PT. J	PILE NO.	COORDINATES			ANGLE TO BATTER		PILE GROUP
				U1	U2	U3	BATTER	SLOPE-H	
1	1	1	1	-21.00	-36.00	0.00	0.00	3.00	1
	1	2	2	-21.00	0.00	0.00	0.00	3.00	1
	1	3	3	-21.00	36.00	0.00	0.00	3.00	1
	2	1	4	21.00	-36.00	0.00	0.00	3.00	1
	2	2	5	21.00	0.00	0.00	0.00	3.00	1
	2	3	6	21.00	36.00	0.00	0.00	3.00	1

## RESULTS FOR SOIL CONDITION NO. 1

ZONE NO.	GRID I	PT. J	LOAD CASE	PILE FORCES ALONG PILE AXES			PILE LOAD FACTORS	
				F1 M1	F2 M2	F3 M3	AXIAL BENDING	COMBINED MAXIMUM
1	1	1	1	.46010E-12	0.	.26352E+03	.878	.878
				0.	.13523E-10	0.	.000	.878
1	1	2	1	.46010E-12	0.	.26352E+03	.878	.878
				0.	.13523E-10	0.	.000	.878
1	1	3	1	.46010E-12	0.	.26352E+03	.878	.878
				0.	.13523E-10	0.	.000	.878
1	2	1	1	.46010E-12	0.	.26352E+03	.878	.878
				0	.13523E-10	0.	.000	.878
1	2	2	1	.46010E-12	0.	.26352E+03	.878	.878
				0	.13523E-10	0	.000	.878
1	2	3	1	.46010E-12	0.	.26352E+03	.878	.878
				0	.13523E-10	0	.000	.878

(Continued)

Table VI.5 (Concluded)

FOR SOIL CONDITION NO. 1 SUM OF PLF = .52705E+01

PILF FOUNDATION COST = 600.00

ARRAY A(NMAX) CONTAINED 87 WORDS.

### Example No. 3 - Dam Sill Monolith Foundation

In this example the program PILEOPT is used to determine the pile layout for a dam sill monolith. The loads and overall dimensions came from dam sill monoliths S3 - S5 of the replacement of Dam No. 26 on the Mississippi River at Alton, Illinois. The plan and elevation views are shown in Fig. VI.4. The monolith is supported by HP 14x73 steel piles that can be battered either upstream or downstream. The ten load cases considered in the design are tabulated in Table VI.6.

Table VI.6 Design Loads of Dam Sill Monolith

Load Case	Q1 (kips)	Q2 (kips)	Q3 (kips)	Q4 (in-kips)	Q5 (in-kips)	Q6 (in-kips)	Overstress Factor
1	15	0	15,933	0	-10,523,964	0	1.0
2	642	0	8,700	0	-5,973,972	0	1.0
3	2,924	0	6,054	0	-3,104,928	0	1.0
4	2,442	0	11,805	0	-7,061,004	0	1.0
5	1,992	0	12,250	0	-7,328,784	0	1.0
6	4,467	0	6,054	0	-3,194,676	0	1.0
7	3,985	0	11,805	0	-7,150,752	0	1.0
8	1,512	0	8,517	0	-5,943,840	0	1.0
9	3,077	0	-2,513	0	2,099,568	0	1.0
10	3,380	0	-1,562	0	1,614,288	0	1.0

The pile foundation is considered as four zones and the zone parameters are selected so that the design obtained by the program PILEOPT could be very similar to the actual layout. The values for the zone parameters that were chosen are listed in Table VI.7.

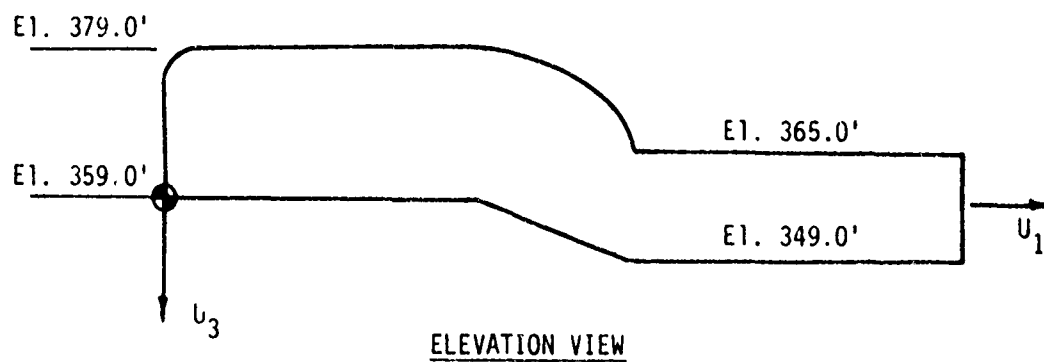
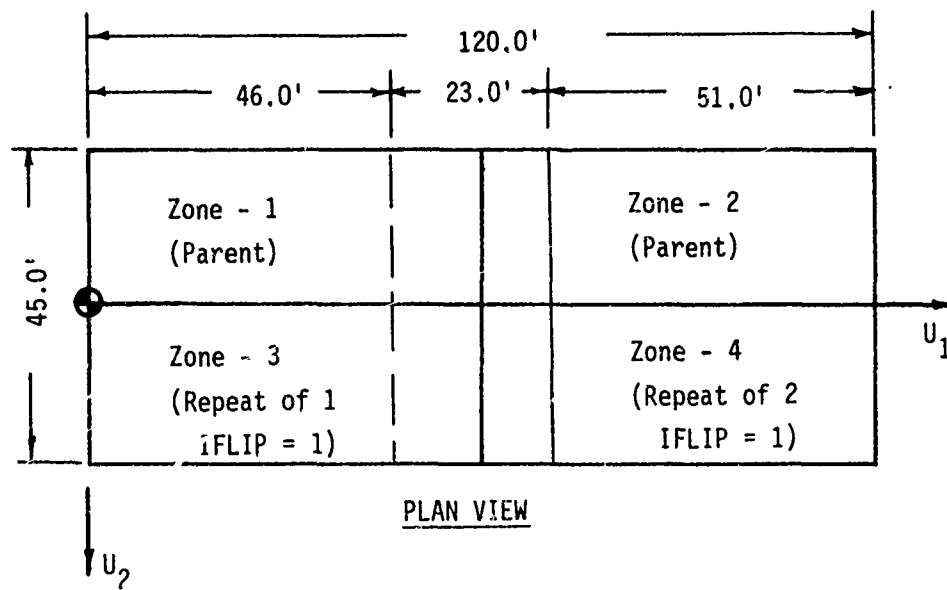


Fig. VI.4 Dam Sill Monolith

Table VI.7 User Selected Zone Parameters  
for Dam Sill Monolith

Parameter	Zone - 1 & 3	Zone - 2 & 4
ZLN-1	720 in.	720 in.
ZLN-2	270 in.	270 in.
BOR-1	30 in.	30 in.
BOR-2	30 in.	60 in.
BOR-3	30 in.	30 in.
BOR-4	60 in.	30 in.
SPL-1	0 in.	0 in.
SPL-2	0 in.	288 in.
SPL-3	0 in.	0 in.
SPL-4	288 in.	0 in.
ALFZN	0 <sup>0</sup>	0 <sup>0</sup>
ALFBT	0 <sup>0</sup>	0 <sup>0</sup>
IFLIP	0 , 1	0 , 1
IRC	2	2
NPB1	1	1
NPB2	1	1
SPA-1 MIN	60 in.	60 in.
SPA-1 MAX	96 in.	120 in.
SPA-2 MIN	60 in.	60 in.
SPA-2 MAX	96 in.	120 in.
H-1 MIN	2:1	2:1
H-1 MAX	100:1	100:1
H-2 MIN	2:1	2:1
H-2 MAX	100:1	100:1
SPA-1 INC	6 in.	6 in.
SPA-2 INC	6 in.	6 in.
SPA-1 INITIAL	60 in.	60 in.
SPA-2 INITIAL	60 in.	60 in.

These values establish the maximum number of piles that could be placed in the foundation. When the spacings are at their minimum values the grids in all zones have 11 rows in the  $U_1$ -direction and 4 columns in

the  $U_2$ -direction. Thus each zone could have as many as 44 piles for a maximum total of 176 piles in the foundation. The maximum spacings produce 7x3 grids in Zones 1 and 3 and 6x2 grids in Zones 2 and 4. The piles are allowed to be battered in the upstream - downstream or  $U_1$ -direction. With the batter pattern parameters  $NPB1 = 1$  and  $NPB2 = 1$  there will be one row (along the  $U_1$ -axis) of piles battered upstream and one row battered downstream. The limits on the batter slopes are set from 2 to 100 so that the range will include the values of 3 and 2.5 that were selected for the actual design. The lower limit of 2 appears to be the lowest value that structural engineers in the Corps will consider in pile designs. The upper limit of 100 is vertical for all practical purposes. The input data for program PILEOPT for this problem is given in Table VI.8.

PILEOPT produced the pile layout presented in Fig. VI.5 for this dam sill monolith. The layout has 36 near vertical piles ( $H = 96.89$ ) and 32 piles battered downstream ( $H = 3.87$ ) in Zones 1 and 3. In Zones 2 and 4 there are 16 near vertical piles ( $H = 97.52$ ) and 20 piles battered downstream ( $H = 4.94$ ). This gives a total of 104 piles in the foundation. These results are for a subgrade modulus of  $n_h = 0.001 \text{ kip/in}^3$ . In the actual design both a strong soil and weak soil were considered. The actual design included 84 piles battered upstream ( $H = 3.00$ ) and 45 piles battered downstream ( $H = 2.50$ ) for a total of 129 piles. The results of PILEOPT appear to compare favorably with the actual design. The output from PILEOPT for this example is given in Table VI.9.

Table VI.8 Input Data for Dam Sill Monolith Problem

10

DAM SILL FOR LOCK 26 7/20/78

0,0,0  
10,4,1,10,1  
001,0 7/2  
1,0,300  
1,0,1,0,1,0  
1,10  
40,30,1  
0 00025  
1, 1000  
224,149,368, 0005, 0005, 001,0,0,0,0,59 3,48 3  
365, 790, 2370, 215,50  
15,0,15933,0,-10523964,0,1  
624,0,8700,0,-5973972,0,1  
2924,0,6054,0,-3104928,0,1  
2442,0,11805,0,-7061004,0,1  
1992,0,12250,0, 7328784,0,1  
4467,0,6054,0,-3194676,0,1  
3985,0,11805,0,-7150752,0,1  
1512,0,8517,0,-5943840,0,1  
3077,0,-2513,0,2099568,0,1  
3380,0, 1562,0,1614288,0,1  
1,0,0  
0,-270,0,0  
720 0,270 ,0 0  
30 0,30,0,30 0,60,0  
0 0,0 0,0,0,288 0  
60 ,60 , 100 0,100 0,0,0  
1,2,1,1  
60 ,96, ,60 ,96  
2 0,100 0,2 0,100,0  
6 0,6 0,0,5,0 5  
1,0,0  
720,-270,0,0  
720,270,0  
30 0,60,0,30,0,30,0  
0 0,288 0,0 0,0 0  
60,60,-100 0,100 0,0 0  
1,2,1,1  
60,120,60,120  
2 0,100,0,2 0,100,0  
6 0 6 0,0,5,0 5  
1,1,1  
0 0,0 0,0 0,0 0  
1,2,1  
720 0,0 0,0 0,0 0

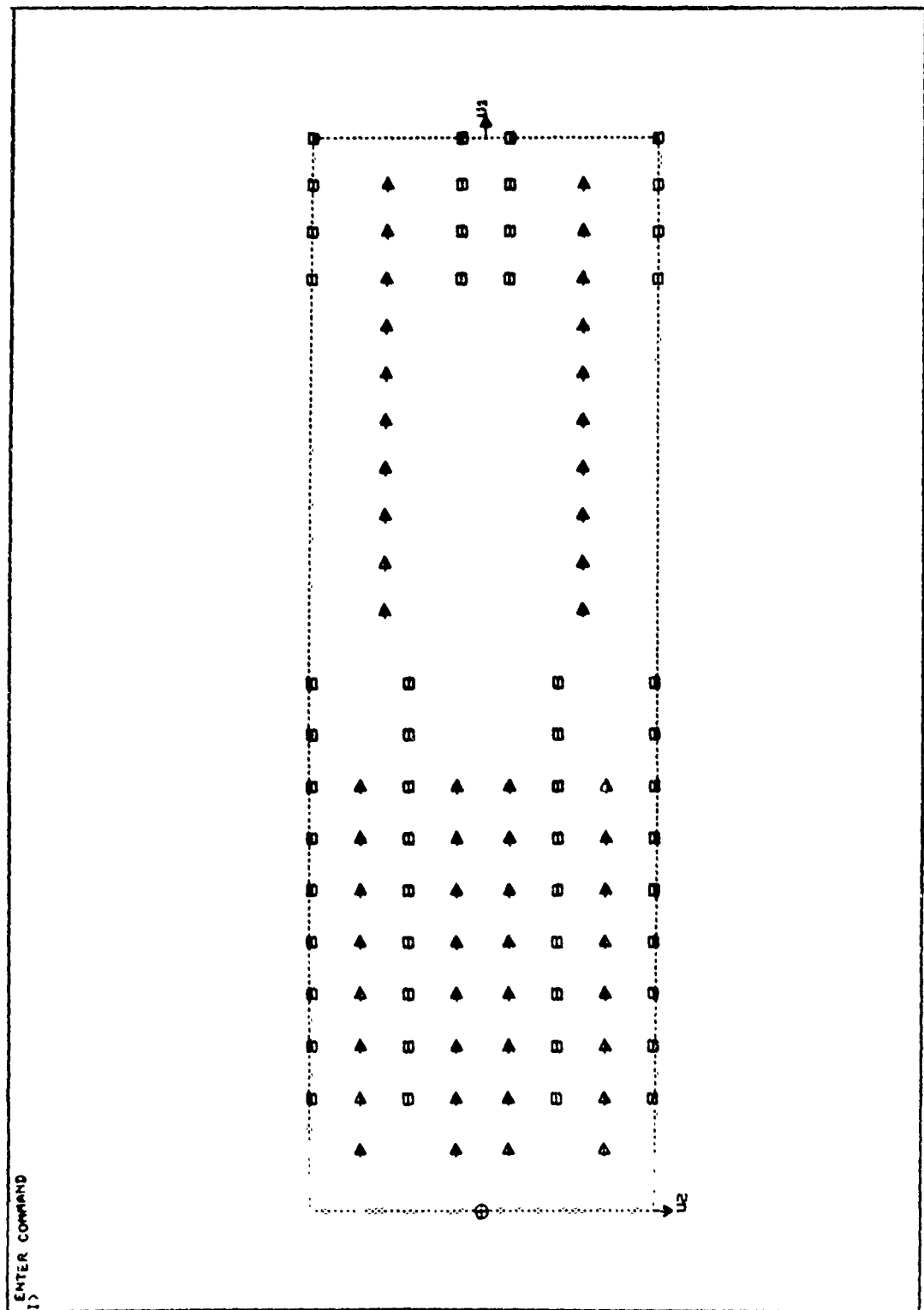


Fig. VI.5 Dam Sill Monolith Pile Layout

Table VI.9 Output from PILEOPT for Dam Sill Monolith Problem

```
***** PROGRAM PILEOPT *****

ANALYSIS AND OPTIMAL DESIGN OF PILE
FOUNDATIONS FOR CONCRETE MONOLITHS

PROBLEM HEADING:

DAM SILL FOR LOCK 26 7/20/78

PRINT LEVEL = 10 (BETWEEN 0 AND 99, MORE AND MORE
                  INTERMEDIATE RESULTS ARE PRINTED.)

PROGRAM FUNCTION SELECTION = 10
  (0 FOR ANALYSIS, GT 0 FOR
   OPTIMAL DESIGN)

NUMBER OF ZONES          = 4
NUMBER OF PILE GROUPS    = 1
NUMBER OF LOAD CASES     = 10

NUMBER OF SOIL COND.     = 1

SOIL CONDITION NO. = 1
SUBGRADE MODULUS = .10000E+02
BENDING MOMENT FACTOR = .77200E+00

OUTPUT CONTROL OPTIONS.
(TABLE ? 0-NO, 1-YES)
JPLG = 0(PILE GEOMETRY)
1FL  = 0(LOCAL FORCES)
IFG  = 0(GLOBAL FORCES)
ICOST = 1(COST EVALUATIONS)
INEAT = 0(ENGINEERING ROUNDING)
NFMAX = 300(MAX NO OF COST EVALUATIONS)

ALLOWABLE DISPLACEMENT
D1 = 1000E+01 D2 = .1000E+01 D3 = .1000E+01

WEIGHT FACTORS FOR OPTIMIZATION
AXIAL PILE LOAD FACTOR = 1.00
```

(Continued)

Table VI.9 (Continued)

BENDING PILE LOAD FACTOR = 10.00

PILE DELETION CONTROL PARAMETERS

MAXIMUM NUMBER OF DELETION PASSES = 40

MAXIMUM PERCENT DELETE = 30.000

MINIMUM PERCENT DELETE = 1.000

CONVERGENCE TOLERANCE = .25000E-03

\*\*\*\*\* PILE GROUP DATA \*\*\*\*\*

GROUP NO 1 PILE COST = 1000.00

MATRIX B IS INPUT FOR THIS GROUP

SOIL CONDITION NO. = 1 NH = .10000E-02

LOCAL STIFFNESS MATRIX B

.224E+03	0.	0.	0.	0.	0.
0.	.149E+03	0.	0.	0.	0.
0.	0.	.368E+03	0.	0.	0.
0.	0.	0.	.500E-03	0.	0.
0.	0.	0.	0.	.500E-03	0.
0.	0.	0.	0.	0.	.100E-02

ALLOWABLE FORCES AND BENDING MOMENTS

FA = 365.0 FB4 = 790.0 FB5 = 2376.0

CALOW = 215.0 TALOW = 50.0

TABLE OF APPLIED LOADS

LOAD CASE	Q1 M1	Q2 M2	Q3 M3	OVERSTRESS FACTOR
1	.15000E+02 0.	0.	15933E+05	1.000
	0.	-.10524E+08 0.		
2	.62400E+03 0.	0.	.87000E+04	1.000
	0.	-.59740E+07 0.		
3	.29240E+04 0.	0.	60540E+04	1.000
	0.	-.31049E+07 0.		
4	.24420E+04 0.	0.	.11805E+05	

(Continued)

Table VI.9 (Continued)

0	-.70610E+07 0.	1.000
5	.19970E+04 0 .12250E+05 0. -.73288E+07 0.	1.000
6	.44670E+04 0. .60540E+04 0. -.31947E+07 0.	1.000
7	.39850E+04 0 .11805E+05 0. -.71508E+07 0	1.000
8	.15120E+04 0. .85170E+04 0. -.59438E+07 0.	1.000
9	.30770E+04 0. -.25130E+04 0. .20996E+07 0.	1.000
10	.33800E+04 0 -.15620E+04 0. .16143E+07 0.	1.000

\*\*\*\*\* FILE ZONE DATA \*\*\*\*\*

ZONE NO	TYPE	REPEAT OF ZONE	FLIP AXIS
1	1	0	0
2	1	0	0
3	1	1	1
4	1	2	1

ZONE NO	ZONE CORNER COORDINATES			INITIAL RADIUS	ROTATION ALPHA-Z
	U2C-1	U2C-2	U2C-3		
1	0.00	-270.00	0.00	0.00	0.00
2	720.00	-270.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	720.00	0.00	0.00	0.00	0.00

ZONE NO	ZONE DIMENSIONS		ZONE BORDERS			
	LENGTH-1	LENGTH-2	BOR 1	BOR 2	BOR 3	BOR 4
1	720.00	270.00	30.00	30.00	30.00	60.00
2	720.00	270.00	30.00	60.00	30.00	30.00
3	720.00	270.00	30.00	30.00	30.00	60.00
4	720.00	270.00	30.00	60.00	30.00	30.00

ZONE SHEET FILE LENGTHS

(Continued)

Table VI 9 (Continued)

NO.	SPL-1	SPL-2	SPL-3	SPL-4
1	0.00	0 00	0.00	288 00
2	0.00	288.00	0.00	0 00
3	0.00	0.00	0.00	288.00
4	0.00	288 00	0 00	0.00

ZONE	INITIAL GRID SPACINGS		INITIAL BATTER SLOPES	
NO.	SPA-1	SPA-2	H-1	H-2
1	60.00	60 00	-100.00	100.00
2	60.00	60.00	-100 00	100 00
3	60.00	60.00	-100 00	100.00
4	60 00	60 00	-100.00	100.00

BATTER PATTERN PARAMETERS				
ZONE	DIR. OF	PATTERN	ANGLE TO	FILE
NO.	CHANGE	NUMBERS N1,N2	BATTER	GROUP
1	2	1, 1	0 00	1
2	2	1, 1	0.00	1
3	2	1, 1	0 00	1
4	2	1, 1	0 00	1

TABLES OF LIMITING VALUES  
(USED FOR OPTIMIZATION)

ZONE	SPA 1 MIN	SPA-1 MAX	SPA 2 MIN	SPA 2 MAX
1	60 00	96 00	60 00	96 00
2	60.00	120 00	60 00	120 00
3	60.00	96.00	60 00	96 00
4	60 00	120 00	60 00	120 00

ZONE	H 1 MIN	H 1 MAX	H-2 MIN	H-2 MAX
1	2 00	100 00	2 00	100 00
2	2 00	100 00	2 00	100 00
3	2 00	100 00	2 00	100 00
4	2 00	100 00	2 00	100 00

ZONE	SPA 1 INC	SPA 2 INC	H 1 INC	H 2 INC
1	6 00	6 00	50	50
2	6 00	6 00	50	50
3	6 00	6 00	50	50
4	6 00	6 00	50	50

SUMMARY OF ZONE RECTANGULAR GRIDS

(Continued)

Table VI.9 (Continued)

## USED IN THE OPTIMIZATION

ZONE NO.	MAX NO. OF ROWS	MAX NO. OF COLS	MAX NO. OF FILES
1	11	4	44
2	11	4	44
3	11	4	44
4	11	4	44

MAX NO. OF FILES IN FOUNDATION = 176

MIN. PERCENT DELETE HAS BEEN INCREASED PDMM = 2.173

NUMBER OF OPTIMIZATION VARIABLES = 4

INITIAL SPACINGS ARE USED FOR  
OPTIMUM BATTER SLOPES CALCULATION

SPACINGS FOR THIS OPTIMIZATION PASS

ZONE	SPA-1	SPA-2
1	.60000E+02	.60000E+02
2	.60000E+02	.60000E+02
3	.60000E+02	.60000E+02
4	.60000E+02	.60000E+02

NF	AXIAL	BLINDING	WEIGHTED	NUMBER OF FILES IN ZONE			
	PLF	PLF	PLF	1	2	3	4
0	74107E+02	86068E+02	93479E+03	44	44	44	44
1	74066E+02	89462E+02	96869E+03	42	44	42	44
2	74063E+02	81884E+02	89290E+03	42	44	42	44
3	74071E+02	87400E+02	94807E+03	42	44	42	44
4	74076E+02	84241E+02	91649E+03	42	42	42	42
5	74575E+02	90831E+02	98288E+03	42	38	42	38
6	74938E+02	84237E+02	91731E+03	42	38	42	38
7	75057E+02	84463E+02	91968E+03	42	38	42	38
8	74089E+02	87422E+02	94831E+03	42	38	42	38
9	74104E+02	85714E+02	93124E+03	42	38	42	38
10	74107E+02	85380E+02	92790E+03	42	38	42	38
11	74098E+02	84517E+02	91921E+03	42	38	42	38
12	74097E+02	84638E+02	92047E+03	42	38	42	38
13	74094E+02	84291E+02	91700E+03	42	38	42	38
14	74094E+02	84277E+02	91687E+03	42	38	42	38
15	74097E+02	84696E+02	92105E+03	42	38	42	38
16	74095E+02	84295E+02	91704E+03	42	38	42	38
17	74098E+02	84461E+02	91870E+03	42	38	42	38
18	74099E+02	84823E+02	92283E+03	42	38	42	38

(Continued)

Table VI.9 (Continued)

19	74086E+02	83582E+02	90991E+03	42	38	42	38
20	74087E+02	83688E+02	91097E+03	42	38	42	38
21	74077E+02	83173E+02	90580E+03	42	38	42	38
22	74075E+02	82952E+02	90360E+03	42	38	42	38
23	74097E+02	85235E+02	92645E+03	42	38	42	38
24	74097E+02	85262E+02	92671E+03	42	38	42	38
25	74105E+02	86173E+02	93584E+03	42	38	42	38
26	74684E+02	74526E+02	81994E+03	42	38	42	38
27	74090E+02	87937E+02	95346E+03	42	38	42	38
28	74074E+02	84128E+02	91535E+03	42	38	42	38
29	74071E+02	84649E+02	92056E+03	42	38	42	38
30	74050E+02	83186E+02	90591E+03	42	38	42	38
31	74046E+02	81940E+02	89344E+03	42	38	42	38
32	74086E+02	85769E+02	93178E+03	42	38	42	38
33	74087E+02	85098E+02	92507E+03	42	38	42	38
34	74101E+02	85940E+02	92350E+03	42	38	42	38
35	74454E+02	79795E+02	87240E+03	42	38	42	38
36	74101E+02	85365E+02	92775E+03	42	38	42	38
37	73651E+02	76846E+02	84212E+03	42	38	42	38
38	73686E+02	77095E+02	84464E+03	42	38	42	38
39	73703E+02	77260E+02	84630E+03	42	38	42	38
40	73703E+02	77275E+02	84645E+03	42	38	42	38
41	74094E+02	84359E+02	91769E+03	42	38	42	38
42	74093E+02	83910E+02	91319E+03	42	38	42	38
43	74097E+02	84279E+02	91689E+03	42	38	42	38
44	74090E+02	78742E+02	86231E+03	42	38	42	38
45	74097E+02	84257E+02	91666E+03	42	38	42	38
46	74093E+02	83840E+02	91249E+03	42	38	42	38
47	74094E+02	84112E+02	91522E+03	42	38	42	38
48	74094E+02	84085E+02	91494E+03	42	38	42	38
49	73691E+02	76905E+02	84274E+03	42	38	42	38
50	74094E+02	84077E+02	91487E+03	42	38	42	38
51	74102E+02	85445E+02	92855E+03	42	38	42	38
52	74102E+02	85474E+02	92884E+03	42	38	42	38
53	74101E+02	85206E+02	92616E+03	42	38	42	38
54	75064E+02	75985E+02	83492E+03	42	38	42	38
55	74101E+02	85210E+02	92620E+03	42	38	42	38
56	73962E+02	78249E+02	85645E+03	42	38	42	38
57	73948E+02	77928E+02	85323E+03	42	38	42	38
58	73945E+02	77857E+02	85251E+03	42	38	42	38
59	74084E+02	77992E+02	85401E+03	42	38	42	38
60	74298E+02	82548E+02	89178E+03	42	38	42	38
61	74209E+02	74959E+02	82380E+03	42	38	42	38
62	73924E+02	82568E+02	89960E+03	42	38	42	38
63	74444E+02	88772E+02	96216E+03	42	38	42	38
64	73945E+02	77852E+02	85246E+03	42	38	42	38
65	73855E+02	77042E+02	84428E+03	42	38	42	38
66	73856E+02	77048E+02	84434E+03	42	38	42	38
67	73783E+02	75987E+02	83365E+03	42	38	42	38
68	73783E+02	76005E+02	83383E+03	42	38	42	38
69	73977E+02	79019E+02	86417E+03	42	38	42	38

(Continued)

Table VI.9 (Continued)

70	73977E+02	79025E+02	86423E+03	42	38	42	38
71	74803E+02	76766E+02	84246E+03	42	38	42	38
72	74804E+02	76788E+02	84268E+03	42	38	42	38
73	74899E+02	78426E+02	85916E+03	42	38	42	38
74	74900E+02	78428E+02	85918E+03	42	38	42	38
75	75215E+02	80873E+02	88394E+03	42	38	42	38
76	74741E+02	77552E+02	85026E+03	42	38	42	38
77	75213E+02	80840E+02	88361E+03	42	38	42	38
78	74746E+02	82957E+02	90432E+03	42	38	42	38
79	74745E+02	82957E+02	90432E+03	42	38	42	38
80	74365E+02	77360E+02	84797E+03	42	38	42	38
81	74368E+02	74510E+02	81967E+03	42	38	42	38
82	74365E+02	77360E+02	84797E+03	42	38	42	38
83	74333E+02	82067E+02	89500E+03	42	38	42	38
84	74327E+02	82064E+02	89497E+03	42	38	42	38
85	74345E+02	81984E+02	89418E+03	42	38	42	38
86	74747E+02	75169E+02	82644E+03	42	38	42	38
87	74351E+02	82029E+02	89464E+03	42	38	42	38
88	74721E+02	74597E+02	82069E+03	42	38	42	38
89	74720E+02	74596E+02	82068E+03	42	38	42	38
90	74630E+02	74530E+02	81993E+03	42	38	42	38
91	74628E+02	74508E+02	81970E+03	42	38	42	38
92	74649E+02	78321E+02	85786E+03	42	38	42	38
93	74651E+02	78322E+02	85787E+03	42	38	42	38
94	74788E+02	82100E+02	89579E+03	42	38	42	38
95	74980E+02	76615E+02	84113E+03	42	38	42	38
96	75082E+02	78764E+02	86272E+03	42	38	42	38
97	74681E+02	74736E+02	82204E+03	42	38	42	38
98	74647E+02	74383E+02	81848E+03	42	38	42	38
99	75084E+02	78768E+02	86277E+03	42	38	42	38
100	74784E+02	82078E+02	89557E+03	42	38	42	38
101	74827E+02	76997E+02	84480E+03	42	38	42	38
102	74827E+02	76997E+02	84480E+03	42	38	42	38
103	74241E+02	74749E+02	82173E+03	42	38	42	38
104	74241E+02	74752E+02	82176E+03	42	38	42	38
105	74248E+02	74794E+02	82218E+03	42	38	42	38
106	74248E+02	74797E+02	82222E+03	42	38	42	38
107	73775E+02	76098E+02	83475E+03	42	38	42	38
108	74277E+02	75320E+02	82748E+03	42	38	42	38
109	73775E+02	76103E+02	83491E+03	42	38	42	38
110	73763E+02	76019E+02	83395E+03	42	38	42	38
111	73762E+02	76011E+02	83387E+03	42	38	42	38
112	74896E+02	75729E+02	83219E+03	42	38	42	38
113	74235E+02	74662E+02	82086E+03	42	38	42	38
114	74896E+02	75726E+02	83216E+03	42	38	42	38
115	74698E+02	78013E+02	85483E+03	42	38	42	38
116	74698E+02	78013E+02	85483E+03	42	38	42	38
117	74111E+02	75939E+02	83350E+03	42	38	42	38
118	74694E+02	74550E+02	82020E+03	42	38	42	38
119	74112E+02	75954E+02	83366E+03	42	38	42	38
120	74242E+02	75148E+02	82572E+03	42	38	42	38

(Continued)

Table VI.9 (Continued)

121	.74241E+02	.75147E+02	.82571E+03	42	38	42	38
122	.74569E+02	.74442E+02	.81899E+03	42	38	42	38
123	.74569E+02	.74440E+02	.81897E+03	42	38	42	38
124	.74548E+02	.74547E+02	.82002E+03	42	38	42	38
125	.74547E+02	.74547E+02	.82001E+03	42	38	42	38
126	.74898E+02	.75073E+02	.82563E+03	42	38	42	38
127	.74684E+02	.74351E+02	.81819E+03	42	38	42	38
128	.74898E+02	.75072E+02	.82562E+03	42	38	42	38
129	.74817E+02	.76023E+02	.83504E+03	42	38	42	38
130	.74817E+02	.76023E+02	.83504E+03	42	38	42	38
131	.74544E+02	.75057E+02	.82512E+03	42	38	42	38
132	.74661E+02	.74395E+02	.81861E+03	42	38	42	38
133	.74544E+02	.75061E+02	.82515E+03	42	38	42	38
134	.74675E+02	.74410E+02	.81877E+03	42	38	42	38
135	.74674E+02	.74409E+02	.81877E+03	42	38	42	38
136	.74209E+02	.74430E+02	.81851E+03	42	38	42	38
137	.74209E+02	.74414E+02	.81834E+03	42	38	42	38
138	.74209E+02	.74418E+02	.81839E+03	42	38	42	38
139	.74210E+02	.74419E+02	.81840E+03	42	38	42	38
140	.74255E+02	.74969E+02	.82394E+03	42	38	42	38
141	.74631E+02	.74384E+02	.81847E+03	42	38	42	38

MINIMUM WTD PLF SUM = .81819E+03

## OPTIMUM BATTER SLOPES

ZONE	H-1 OPT	H-2 OPT
1	.76391E+02	.38705E+01
2	.97524E+02	.49352E+01
3	.96891E+02	.38705E+01
4	.97524E+02	.49352E+01

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.60000E+02	.60000E+02
2	.60000E+02	.60000E+02
3	.60000E+02	.60000E+02
4	.60000E+02	.60000E+02

## DELETING THE LEAST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	11	4	44	632	1

(Continued)

Table VI.9 (Continued)

2	11	4	42	.515	1
3	11	4	44	.632	1
4	11	4	42	.515	1
1	11	4	44	.658	2
2	11	4	30	.677	2
3	11	4	44	.658	2
4	11	4	30	.677	2
1	11	4	32	.883	3
2	11	4	30	.741	3
3	11	4	32	.883	3
4	11	4	30	.741	3
1	11	4	32	.958	4
2	11	4	23	.888	4
3	11	4	32	.958	4
4	11	4	23	.888	4
1	11	4	32	.883	5
2	11	4	30	.741	5
3	11	4	32	.883	5
4	11	4	30	.741	5
1	11	4	29	.988	6
2	11	4	26	.869	6
3	11	4	29	.988	6
4	11	4	26	.869	6
1	11	4	32	.883	7
2	11	4	30	.741	7
3	11	4	32	.883	7
4	11	4	30	.741	7
1	11	4	30	.941	8
2	11	4	28	.808	8
3	11	4	30	.941	8
4	11	4	28	.808	8
1	11	4	32	.883	9
2	11	4	30	.741	9
3	11	4	32	.883	9
4	11	4	30	.741	9
1	11	4	31	.911	10
2	11	4	29	.773	10
3	11	4	31	.911	10
4	11	4	29	.773	10

SWEEP = 10 FAILED BACK UP TO SWEEP 9

DELETION TERMINATED PERIODIC PUNN

NO OF FILES = 124

EXCESS FILE = 0

MAX DISK - 1595E100 1387E 14 44/9E100

PFCOST = 124000 00

OBTAINED BY DELETING THE LEAST LOADED FILES

TIME REQUIRED FOR THIS DELETION = 4 00

DELETING THE MOST LOADED FILES

(Continued)

Table VI.9 (Continued)

***** PILE DELFTION *****					
ZONE	NI	NJ	PILES	AVE PLF	ISW
1	11	4	44	.632	1
2	11	4	42	.515	1
3	11	4	44	.632	1
4	11	4	42	.515	1
1	11	4	44	.700	2
2	11	4	30	.620	2
3	11	4	44	.700	2
4	11	4	30	.620	2
1	11	4	44	.772	3
2	11	4	21	.738	3
3	11	4	44	.772	3
4	11	4	21	.738	3
1	11	4	34	1.008	4
2	11	4	17	.894	4
3	11	4	34	1.008	4
4	11	4	17	.894	4
1	11	4	44	.772	5
2	11	4	21	.738	5
3	11	4	44	.772	5
4	11	4	21	.738	5
1	11	4	38	.914	6
2	11	4	18	.822	6
3	11	4	38	.914	6
4	11	4	18	.822	6
1	11	4	35	1.023	7
2	11	4	16	.868	7
3	11	4	35	1.023	7
4	11	4	16	.868	7
1	11	4	38	.914	8
2	11	4	18	.822	8
3	11	4	38	.914	8
4	11	4	18	.822	8
1	11	4	36	.982	9
2	11	4	17	.841	9
3	11	4	36	.982	9
4	11	4	17	.841	9
1	11	4	38	.914	10
2	11	4	18	.822	10
3	11	4	38	.914	10
4	11	4	18	.822	10
1	11	4	37	.942	11
2	11	4	18	.820	11
3	11	4	37	.942	11
4	11	4	18	.820	11
1	11	4	36	.972	12
2	11	4	18	.816	12
3	11	4	36	.972	12
4	11	4	18	.816	12

(Continued)

Table VI.9 (Continued)

SWEEP = 12 FAILED BACK-UP TO SWEEP = 11  
 DELETION TERMINATION PLRILY ) PMN  
 NO OF FILES = 110  
 EXCESS PLF = 0  
 MAX DISPL. = 1695E+00 .4380E 15 .4561E+00  
 PFCOST = 110000 00  
 OBTAINED BY DELETING THE MOST LOADED FILES.  
 TIME REQUIRED FOR THIS DELETION = 4.861

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.66000E+02	.60000E+02
2	.60000E+02	.60000E+02
3	.66000E+02	.60000E+02
4	.60000E+02	.60000E+02

DELETING THE MOST LOADED FILES

\*\*\*\*\* FILE DELETION \*\*\*\*\*

ZONE	N1	NJ	FILES	AVG PLF	TSN
1	10	4	40	680	1
2	11	4	42	536	1
3	10	4	40	680	1
4	11	4	42	536	1
1	10	4	40	680	2
2	11	4	42	536	2
3	10	4	40	680	2



NOTE: THE BALANCE OF THIS CALCULATION AND  
 SEVERAL INTERVENING CALCULATIONS  
 HAVE BEEN OMITTED.

(Contin. J)

Table VI.9 (Continued)

4	11	3	18	.885	4
1	10	4	34	.954	5
2	11	3	17	.981	5
3	10	4	34	.954	5
4	11	3	17	.981	5
1	10	4	40	.842	6
2	11	3	18	.885	6
3	10	4	40	.842	6
4	11	3	18	.885	6
1	10	4	34	.954	7
2	11	3	17	.981	7
3	10	4	34	.954	7
4	11	3	17	.981	7
1	10	4	40	.842	8
2	11	3	18	.885	8
3	10	4	40	.842	8
4	11	3	18	.885	8
1	10	4	37	.889	9
2	11	3	17	.968	9
3	10	4	37	.889	9
4	11	3	17	.968	9
1	10	4	40	.842	10
2	11	3	18	.885	10
3	10	4	40	.842	10
4	11	3	18	.885	10
1	10	4	39	.855	11
2	11	3	18	.898	11
3	10	4	39	.855	11
4	11	3	18	.898	11
1	10	4	38	.868	12
2	11	3	18	.911	12
3	10	4	38	.868	12
4	11	3	18	.911	12
1	10	4	37	.883	13
2	11	3	18	.924	13
3	10	4	37	.883	13
4	11	3	18	.924	13
1	10	4	36	.899	14
2	11	3	18	.937	14
3	10	4	36	.899	14
4	11	3	18	.937	14
1	10	4	35	.923	15
2	11	3	18	.937	15
3	10	4	35	.923	15
4	11	3	18	.937	15
1	10	4	34	.949	16
2	11	3	18	.937	16
3	10	4	34	.949	16
4	11	3	18	.937	16

(Continued)

Table VI.9 (Continued)

1	10	4	33	.977	17
2	11	3	18	.939	17
3	10	4	33	.977	17
4	11	3	18	.939	17

SWEEP = 17 FAILED BACK-UP TO SWEEP = 16  
 DELETION TERMINATED. PERMIT TO PUNCH.  
 NO. OF FILES = 104  
 EXCESS PLF = 0.  
 MAX. DISPL. = .1807E+00 .1427E+14 .4669E+00  
 PFCOST = 104000 00  
 OBTAINED BY DELETING THE MOST LOADED FILES.  
 TIME REQUIRED FOR THIS DELETION = 7 257

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA 1	SPA 2
1	.66000E+02	.66000E+02
2	.60000E+02	10800E+03
3	.66000E+02	.66000E+02
4	.60000E+02	10800E+03

## DELETING THE LEAST LOADED FILES

## \*\*\*\*\* FILE DELETION \*\*\*\*\*

ZONE	NI	NJ	FILES	AVE PLF	ISW
1	10	4	40	793	1
2	11	2	21	856	1
3	10	4	40	793	1
4	11	2	21	856	1
1	10	4	40	793	2
2	11	2	21	856	2
3	10	4	40	793	2
4	11	2	21	856	2
1	10	4	40	793	3
2	11	2	21	856	3
3	10	4	40	793	3
4	11	2	21	856	3
1	10	4	28	1 104	4
2	11	2	21	925	4
3	10	4	28	1 104	4
4	11	2	21	925	4
1	10	4	40	793	5
2	11	2	21	856	5
3	10	4	40	793	5
4	11	2	21	856	5
1	10	4	34	964	6
2	11	2	19	905	6
3	10	4	34	964	6

(Continued)

Table VI.9 (Continued)

4	11	2	19	.905	6
1	10	4	40	.793	7
2	11	2	21	.856	7
3	10	4	40	.793	7
4	11	2	21	.856	7
1	10	4	37	.873	8
2	11	2	20	.877	8
3	10	4	37	.873	8
4	11	2	20	.877	8
1	10	4	35	.937	9
2	11	2	19	.903	9
3	10	4	35	.937	9
4	11	2	19	.903	9
1	10	4	37	.873	10
2	11	2	20	.877	10
3	10	4	37	.873	10
4	11	2	20	.877	10
1	10	4	36	.898	11
2	11	2	20	.877	11
3	10	4	36	.898	11
4	11	2	20	.877	11
1	10	4	35	.923	12
2	11	2	20	.879	12
3	10	4	35	.923	12
4	11	2	20	.879	12
1	10	4	34	.949	13
2	11	2	20	.882	13
3	10	4	34	.949	13
4	11	2	20	.882	13

SWEEP = 13 FAILED BACK-UP TO SWEEP = 12

DELETION TERMINATED PERMIT ) PMN

NO OF FILES = 110

EXCESS PLF = 0

MAX. DISPL. = .1738E+00 .2098E-14 .4157E+00

PFCOST = 110000.00

OBTAINED BY DELETING THE LEAST LOADED FILES

TIME REQUIRED FOR THIS DELETION = 4.976

DELETING THE MOST LOADED FILES

\*\*\*\*\* FILE DELETION \*\*\*\*\*

ZONE	NI	NJ	FILES	AVE PLF	ISW
1	10	4	40	.793	1
2	11	2	21	.856	1
3	10	4	40	.793	1
4	11	2	21	.856	1
1	10	4	40	.793	2
2	11	2	21	.856	2
3	10	4	40	.793	2

(Continued)

Table VI.9 (Continued)

4	11	2	21	.856	2
1	10	4	40	.793	3
2	11	2	21	.856	3
3	10	4	40	.793	3
4	11	2	21	.856	3
1	10	4	28	1 104	4
2	11	2	21	.925	4
3	10	4	28	1 104	4
4	11	2	21	.925	4
1	10	4	40	.793	5
2	11	2	21	.856	5
3	10	4	40	.793	5
4	11	2	21	.856	5
1	10	4	34	.893	6
2	11	2	19	.993	6
3	10	4	34	.893	6
4	11	2	19	.993	6
1	10	4	40	.793	7
2	11	2	21	.856	7
3	10	4	40	.793	7
4	11	2	21	.856	7
1	10	4	37	.838	8
2	11	2	20	.923	8
3	10	4	37	.838	8
4	11	2	20	.923	8
1	10	4	40	.793	9
2	11	2	21	.856	9
3	10	4	40	.793	9
4	11	2	21	.856	9
1	10	4	39	.804	10
2	11	2	21	.869	10
3	10	4	39	.804	10
4	11	2	21	.869	10
1	10	4	38	.815	11
2	11	2	21	.882	11
3	10	4	38	.815	11
4	11	2	21	.882	11
1	10	4	37	.835	12
2	11	2	21	.883	12
3	10	4	37	.835	12
4	11	2	21	.883	12
1	10	4	36	.856	13
2	11	2	21	.883	13
3	10	4	36	.856	13
4	11	2	21	.883	13
1	10	4	35	.879	14
2	11	2	21	.885	14
3	10	4	35	.879	14
4	11	2	21	.885	14
1	10	4	34	.904	15
2	11	2	21	.886	15

(Continued)

Table VI.9 (Continued)

3	10	4	34	.904	15
4	11	2	21	.886	15
1	10	4	33	.930	16
2	11	2	21	.889	16
3	10	4	33	.930	16
4	11	2	21	.889	16
1	10	4	32	.959	17
2	11	2	21	.892	17
3	10	4	32	.959	17
4	11	2	21	.892	17
1	10	4	31	.988	18
2	11	2	21	.896	18
3	10	4	31	.988	18
4	11	2	21	.896	18

SWEEP = 18 FAILED BACK UP TO SWEEP = 17

DELETION TERMINATED: PERILT &gt; PIMN

NO. OF FILES = 106

EXCESS PIF = 0.

MAX. DISPL. = .1756E+00 2222E-14 .4366E+00

PFCOST = 106000.00

OBTAINED BY DELETING THE MOST LOADED FILES.

TIME REQUIRED FOR THIS DELETION = 7.421

ZONE NO. 3 IS A REPEAT OF ZONE NO. 1

ZONE NO. 4 IS A REPEAT OF ZONE NO. 2

## CPU TIME

OPTIMUM BATTER SLOPE PHASE 76.893 SECONDS

FILE DELETION PHASE 142.813 SECONDS

## \*\*\*\*\* OPTIMIZATION RESULTS \*\*\*\*\*

OPTIMUM PILE FOUNDATION COST = 104000.00

ZONE NO.	OPTIMUM SPACINGS		OPTIMUM BATTER SLOPES	
	SFA-1	SFA-2	H-1	H-2
1	.66000E+02	.66000E+02	.96891E+02	.38705E+01
2	.60000E+02	.10200E+03	.97524E+02	.49352E+01
3	.66000E+02	.66000E+02	.96891E+02	.38705E+01

(Continued)

Table VI.9 (Continued)

4 .60000E+02 .10200E+03 -.97524E+02 .49352E+01

PLACEMENT OF PILES IN ZONES

PILES WERE DELETED FROM ZONE 1

AT GRID PT I , J

1	1
1	3
9	2
9	4
10	2
10	4

ZONE 1 HAS 10 ROWS, 4 COLS, 34 PILES WITH 6 DELETED.

PILES WERE DELETED FROM ZONE 2

AT GRID PT I , J

1	1
1	3
2	1
2	3
3	1
3	3
4	1
4	3
5	1
5	3
6	1
6	3
7	1
7	3
11	2

ZONE 2 HAS 11 ROWS, 3 COLS, 18 PILES WITH 15 DELETED

PILES WERE DELETED FROM ZONE 3

AT GRID PT I , J

1	1
1	3
9	2
9	4
10	2
10	4

ZONE 3 HAS 10 ROWS, 4 COLS, 34 PILES WITH 6 DELETED

(Continued)

Table VI.9 (Continued)

PILES WERE DELETED FROM ZONE 4  
AT GRID PT. I , J

1	1
1	3
2	1
2	3
3	1
3	3
4	1
4	3
5	1
5	3
6	1
6	3
7	1
7	3
11	2

ZONE 4 HAS 11 ROWS, 3 COLS, 18 PILES WITH 15 DELETED.

TOTAL NUMBER OF PILES = 104

SOIL CONDITION NO. 1  
STIFFNESS MATRIX S

.2370E+05	0.	.1599E+04	-.2369E-08	-.8731E+06	.2590E-07
0.	1550E+05	0.	0	0.	9786E+07
.1599E+04	0	.3787E+05	5710E-07	-.2396E+08	.2369E-08
-.2369E-08	0	5710E-07	9018E+09	-.5722E-05	-.2427E+08
-.8731E+06	0	-.2396E+08	-.7629E-05	.2153E+11	3432E-06
.2590E-07	.9786E+07	.2369E-08	-.2427E+08	1644E-06	9339E+10

FLEXIBILITY MATRIX F

4232E-04	.2167E-18	-.2372E-05	2443E-21	-.9243E-09	-.3432E-21
.2168E-18	1908E-03	.5780E-19	-.5380E-08	.7323E-22	-.1999E-06
-.2372E-05	.6034E-19	.8946E-04	-.4832E-20	9949E-07	-.9555E-22
2463E-21	-.5380E-08	-.5042E-20	.1109E-08	-.5308E-23	8520E-11
-.9243E-09	.7724E-22	.9949E-07	-.4976E-23	.1572E-09	-.1223E-24
-.3433E-21	-.1999E-06	-.9153E-22	.8520E-11	-.1160E-24	3166E-09

RESULTS FOR SOIL CONDITION NO. 1

LOAD	FILE CAP DISPLACEMENTS						
CASE	D1	D2	D3	D4	D5	D6	DMAX

(Continued)

Table VI.9 (Concluded)

1	- 274E-01	.154E-15	378E+00	-.245E-16	-.689E-04	- 243E-18	478E+00
2	113E-01	.201E-15	.182E+00	-.120E-16	-.740E-04	- 318E-18	.289E+00
3	.112E+00	.756E-15	.226E+00	- .133E-16	.112E-03	- .120E-17	.252E+00
4	819E-01	.695E-15	348E+00	- 214E-16	.624E-04	- 110E-17	.357E+00
5	.620E-01	.603E-15	362E+00	-.224E-16	.650E-04	- 955E-18	.367E+00
6	178E+00	108E-14	213E+00	-.125E-16	.961E-04	.172E-17	.277E+00
7	147E+00	102E-14	335E+00	-.206E-16	.469E-04	- .162E-17	.366E+00
8	493E-01	.385E-15	167E+00	-.110E-16	-.883E-04	- 609E-18	.298E+00
9	134E+00	.676E-15	.232E-01	.228E-17	.771E-04	- 107E-17	.190E+00
10	145E+00	.761E-15	128E-01	.140E-18	.952E-04	.120E-17	.191E+00

FOR SOIL CONDITION NO 1 SUM OF PLF = 98267E+02

PILE FOUNDATION COST = 104000 00

ARRAY A(NMAX) CONTAINED 203 WORDS.

#### Example No. 4 - Lock Gate Monolith Foundation

In this example the program PILEOPT is used to determine the pile layout for a lock gate monolith. The loads and overall dimensions came from a preliminary design of a lock gate monolith. A sketch of the lock gate monolith is shown in Fig. VI.6. The monolith is supported by HP 14x73 steel piles. A strong soil with a subgrade modulus of  $0.03 \text{ kip/in}^3$  is considered. The eight sets of design loads are given in Table VI.10.

Table VI.10 Design Loads for Lock Gate Monolith

Load Case	Q1 (kips)	Q2 (kips)	Q3 (kips)	Q4 (in-kips)	Q5 (in-kips)	Q6 (in-kips)	Overstress Factor
1	8,904	0	43,806	-15,429,816	149,448	3,205,440	1.00
2	8,118	-888	16,738	-6,701,040	-2,441,328	2,922,480	1.00
3	8,118	0	23,735	-8,573,580	-2,441,480	2,922,480	1.00
4	8,118	-888	26,684	-10,281,528	-2,441,328	2,922,480	1.00
5	8,118	-1,001	13,918	-5,767,896	-2,441,328	2,922,480	1.33
6	8,118	-1,001	27,771	-10,754,940	-2,441,328	2,922,480	1.33
7	8,118	0	13,282	-4,800,888	-2,441,328	2,922,480	1.33
8	8,118	0	18,060	-6,311,200	-2,957,124	2,922,480	1.33

The pile foundation is considered as three zones and the zone parameters are selected so that the design obtained by PILEOPT could be very similar to the preliminary design. The values of the zone parameters that were chosen are listed in Table VI.11.

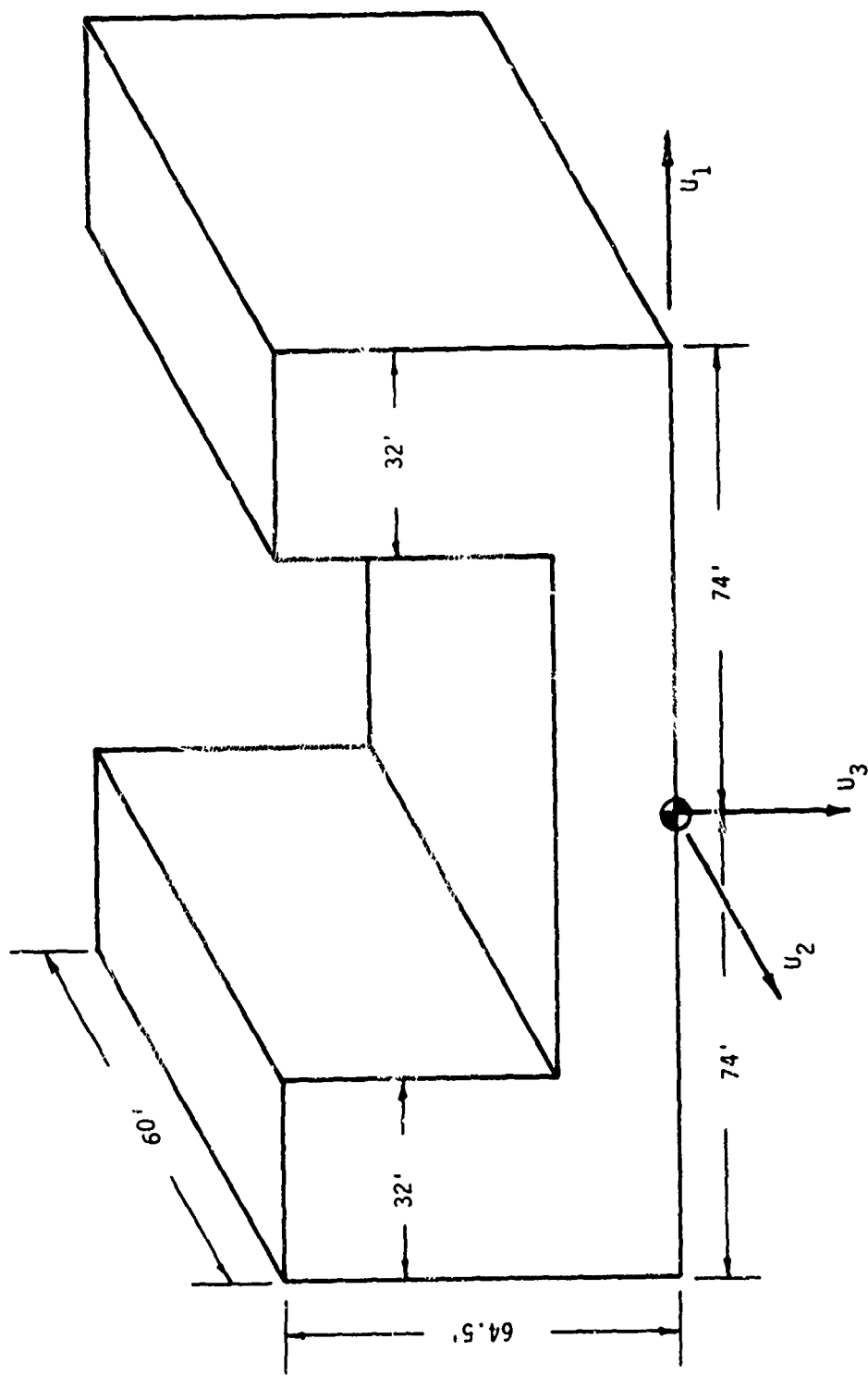


Fig. VI.6 Lock Gate Monolith

Table VI.11 User Selected Zone Parameters  
for Lock Gate Monolith

Parameter	Zone - 1	Zone - 2	Zone - 3
ZLN-1	504 in.	504 in.	504 in.
ZLN-2	720 in.	720 in.	720 in.
BOR-1	36 in.	36 in.	36 in.
BOR-2	18 in.	18 in.	18 in.
BOR-3	36 in.	36 in.	36 in.
BOR-4	18 in.	18 in.	18 in.
ALFZN	0°	0°	0°
ALFBT	0°	90°	0°
IFLIP	0	0	0
IRC	2	1	2
NPB1	1	1	1
NP32	1	1	1
SPA-1 MIN	48 in.	48 in.	48 in.
SPA-1 MAX	72 in.	72 in.	72 in.
SPA-2 MIN	48 in.	48 in.	48 in.
SPA-2 MAX	72 in.	72 in.	72 in.
H-1 MIN	2:1	2:1	2:1
H-1 MAX	100:1	100:1	100:1
H-2 MIN	2:1	2:1	2:1
H-2 MAX	100:1	100:1	100:1
SPA-1 INC	12 in.	12 in.	12 in.
SPA-2 INC	12 in.	12 in.	12 in.
SPA-1 INITIAL	72 in.	72 in.	72 in.
SPA-2 INITIAL	72 in.	72 in.	72 in.

These values establish the maximum number of piles that could be placed in the foundation. With the minimum spacings the grids in all zones have 10 rows in the  $U_1$ -directions and 14 columns in the  $U_2$ -direction. Thus each zone could have as many as 140 piles for a total of 420 piles in the foundation. The maximum spacings of 72 inches are used as the initial spacings so that a minimum number of piles are in the foundation during Phase I of the optim-

ization in which the optimum batter slopes are determined. During Phase I there are 70 piles in each zone or a total of 210 piles in the foundation. In each zone the batter slopes are allowed to be between 2 and 100. In the outboard zones 1 and 3 the piles can be battered in the  $U_1$ -direction while the piles in the central zone are to be battered in the  $U_2$ -direction. The input data for program PILEOPT for this problem is given in Table VI.12.

The pile layout in Fig. VI.7 was produced by PILEOPT for this lock gate monolith. In Zone-1 there are 49 near vertical piles ( $H = -28.05$ ) and 67 piles battered in the  $U_1$ -direction ( $H = 2.00$ ). There are 30 near vertical piles ( $H = 23.26$ ) and 26 piles battered in the negative  $U_2$ -direction ( $H = -4.52$ ) in Zone-2. Zone-3 has 48 near vertical piles ( $H = -30.72$ ) and 68 piles battered in the  $U_1$ -direction ( $H = 2.07$ ). This gives a total of 288 piles in the layout obtained by PILEOPT to support the lock gate monolith. The preliminary design considered both a weak soil ( $n_h = 0.005 \text{ kip/in}^3$ ) and the strong soil ( $n_h = 0.03 \text{ kip/in}^3$ ) considered here. The preliminary design had 387 piles in the foundation. Part of the output from PILEOPT for this example is given in Table VI.13

Table VI.12 Input Data for Lock Gate Monolith Problem

```

10
  LOCK GATE MONOLITH PILE FOUNDATION 7-5-78
0,0,0
1,3,1,8,1
0 03,0.772
1,0,500
1,1,1
1,10
40,30,1
1,1000
3E4,734,262,21 5,624
1.075,0.5,1.5,0.0,1.0,1 0
365,790,2376,215,50
8904,0,42806,-15429816,149448,3205440,1
8118,-888,16738,-6701040 -2441328,2922480,1
8118,0,23735,-8573580,-2441328,2922480,1
8118,-888,26684,-10281528,-2441328,2922480,1
8118,-1001,13918,-5767896,-2441328,2922480,1.33
8118,-1001,27771,-10754940,-2441328,2922480,1.33
8118,0,13282,-4800888,-2441328,2922480,1 33
8118,0,18060,-6331200,-2957124,2922480,1 33
1,0,0
-756,-720,0,0
504,720,0
36,18,36,18
0,0,0,0
72,72,-3,3,0
1,2,1,1
48,72,48,72
2,100,2,100
12,12,25,25
1,0,0
-252,-720,0,0
504,720,0
36,18,36,18
0,0,0,0
72,72,-3,3,90
1,1,1,1
48,72,48,72
2,100,2,100
12,12,25,25
1,0,0
-252,-720,0,0
504,720,0
36,18,36,18
0,0,0,0
72,72,3,-3,0
1,2,1,1
48,72,48,72
2,100,2,100
12,12,25,25

```

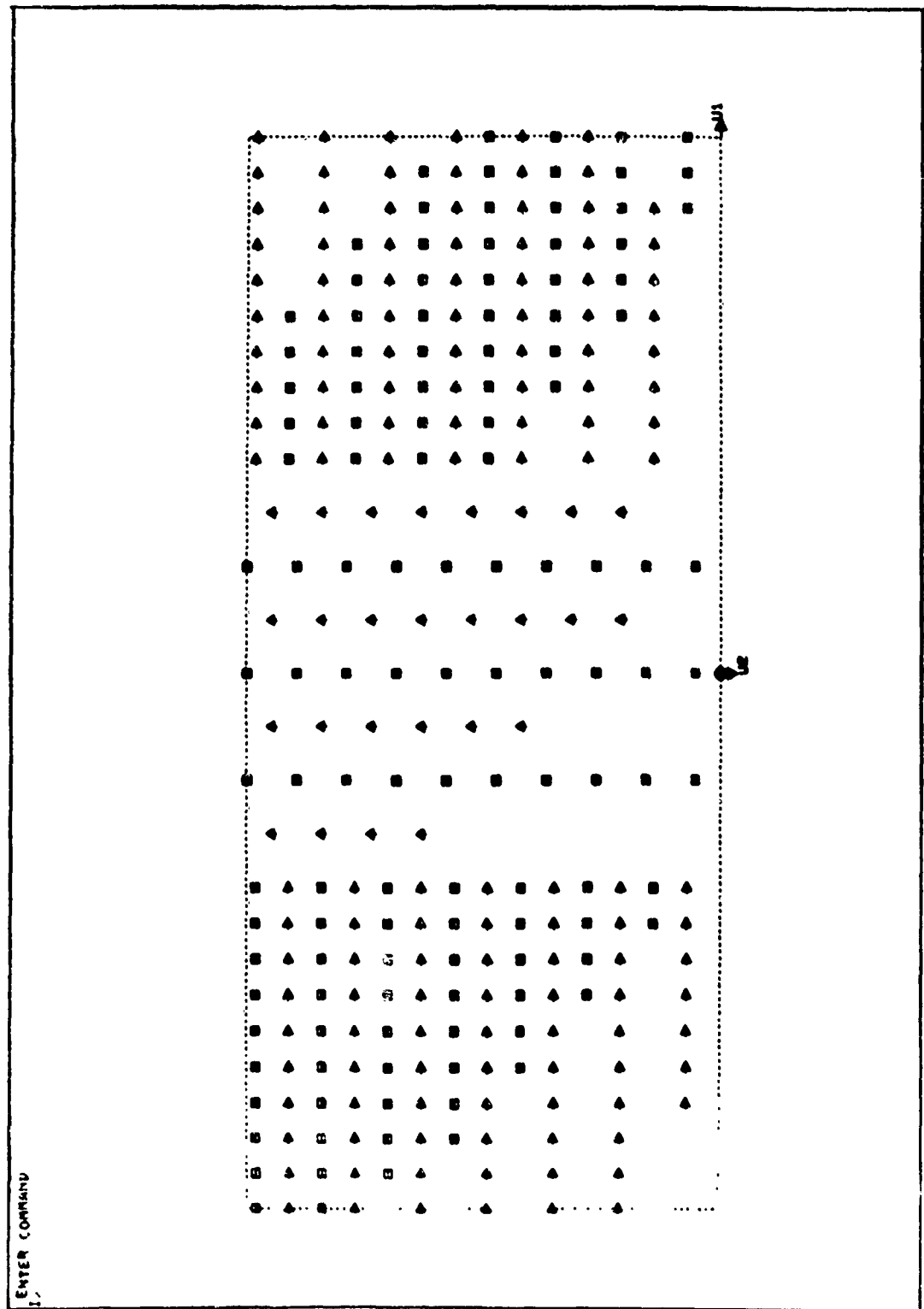


Fig. VI.7 Lock Gate Monolith Pile Layout

Table VI.13 Output from PILEOPT for Lock Gate Monolith Problem

\*\*\*\*\* PROGRAM PILEOPT \*\*\*\*\*

ANALYSIS AND OPTIMAL DESIGN OF PILE  
FOUNDATIONS FOR CONCRETE MONOLITHS

PROBLEM HEADING.

LOCK GATE MONOLITH PILE FOUNDATION 7-5-78

PRINT LEVEL = 10 (BETWEEN 0 AND 99, MORE AND MORE  
INTERMEDIATE RESULTS ARE PRINTED)

PROGRAM FUNCTION SELECTION = 1  
(0 FOR ANALYSIS, GT 0 FOR  
OPTIMAL DESIGN)

NUMBER OF ZONES = 3  
NUMBER OF PILE GROUPS = 1  
NUMBER OF LOAD CASES = 8

NUMBER OF SOIL COND. = 1

SOIL CONDITION NO = 1  
SUBGRADE MODULUS = .30000E-01  
BENDING MOMENT FACTOR = 77200E+00

OUTPUT CONTROL OPTIONS  
(TABLE ? 0-NO, 1-YES)  
IPLG = 0(PILE GEOMETRY)  
IFL = 0(LOCAL FORCES)  
IFG = 0(GLOBAL FORCES)  
ICOST = 1(COST EVALUATIONS)  
INEAT = 0(ENGINEERING ROUNDING)  
NFMAX = 500(MAX NO OF COST EVALUATIONS)

ALLOWABLE DISPLACEMENT  
D1 = 1000E+01 D2 = 1000E+01 D3 = 1000E+01

WEIGHT FACTORS FOR OPTIMIZATION  
AXIAL PILE LOAD FACTOR = 1.00

(Continued)

Table VI.13 (Continued)

BENDING PIPE LOAD FACTOR = 10.00

PIPE DELETION CONTROL PARAMETERS  
 MAXIMUM NUMBER OF DELETION PASSES = 40  
 MAXIMUM PERCENT DELETE = 30.000  
 MINIMUM PERCENT DELETE = 1.000

\*\*\*\*\* PIPE GROUP DATA \*\*\*\*\*

GROUP NO 1 PIPE COST = 1000.00  
 E = 300E+05 IX = 734.0000 IY = 262.0000  
 AREA = 21.5000 LENGTH = 624.0000  
 K1 = 1.075 K2 = .500 K3 = 1.500  
 K4 = 0.000 K5 = 1.000 K6 = 1.000

SOIL CONDITION NO. = 1 NH = 30000E+01  
 LOCAL STIFFNESS MATRIX B  

.113E+03	0.	0.	0.	626E+04	0
0.	751E+02	0.	-.337E+04	0.	0
0.	0	.517E+03	0.	0.	0.
0.	-.337E+04	0.	244E+06	0	0
.626E+04	0.	0	0	557E+06	0
0	0	0	0.	0.	0

ALLOWABLE FORCES AND BENDING MOMENTS  
 FA = 365.0 FB4 = 790.0 FB5 = 2376.0  
 CALOW = 215.0 TALOW = 50.0

TABLE OF APPLIED LOADS					OVERSTRESS FACTOR
LOAD CASE	Q1 M1	Q2 M2	Q3 M3		
1	89040E+04 0 15430E+08	14945E+06	.42806E+05 32054E+07		1.000
2	81180E+04 - - 67010E+07	88800E+03 24413E+07	16738E+05 .29225E+07		1.000
3	81180E+04 0 - 85736E+07	24413E+07	23735E+05 .29225E+07		1.000
4	81180E+04 -	88800E+03	26684E+05		

(Continued)

Table VI.13 (Continued)

	-.10282E+08	-.24413E+07	.29225E+07	1.000
5	.81180E+04	-.10010E+04	.13918E+05	
	-.57679E+07	-.24413E+07	.29225E+07	1.330
6	.81180E+04	-.10010E+04	.27771E+05	
	-10755E+08	-.24413E+07	.29225E+07	1.330
7	.81180E+04	0.	.13282E+05	
	-.48009E+07	-.24413E+07	.29225E+07	1.330
8	.81180E+04	0	.18060E+05	
	-63312E+07	-.29571E+07	.29225E+07	1.330

\*\*\*\*\* PILE ZONE DATA \*\*\*\*\*

ZONE NO	TYPE	REPEAT OF ZONE	FLIP AXIS
1	1	0	0
2	1	0	0
3	1	0	0

ZONE NO	ZONL CORNER COORDINATES			INITIAL RADIUS	ROTATION ALPHA Z
	UZC-1	UZC-2	UZC-3		
1	756.00	-720.00	0.00	0.00	0.00
2	-252.00	-720.00	0.00	0.00	0.00
3	252.00	720.00	0.00	0.00	0.00

ZONE NO	ZONE DIMENSIONS		ZONE BORDERS			
	LENGTH-1	LENGTH-2	BOR-1	BOR-2	BOR-3	BOR-4
1	504.00	720.00	36.00	18.00	36.00	18.00
2	504.00	720.00	36.00	18.00	36.00	18.00
3	504.00	720.00	36.00	18.00	36.00	18.00

ZONE NO.	SHEET PILE LENGTHS			
	SPL-1	SPL-2	SPL-3	SPL-4
1	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00

ZONE NO	INITIAL GRID SPACINGS		INITIAL BATTER SLOPES	
	SPA-1	SPA-2	H-1	H-2

(Continued)

Table VI.13 (Continued)

1	72.00	72.00	-3.00	3.00
2	72.00	72.00	-3.00	3.00
3	72.00	72.00	3.00	-3.00

ZONE NO.	BATTER PATTERN PARAMETERS			
	DIR. OF CHANGE	PATTERN NUMBERS N1, N2	ANGLE TO BATTER	FILE GROUP
1	2	1, 1	0.00	1
2	1	1, 1	90.00	1
3	2	1, 1	0.00	1

TABLES OF LIMITING VALUES  
(USED FOR OPTIMIZATION)

ZONE	SPA-1 MIN	SPA-1 MAX	SPA-2 MIN	SPA-2 MAX
1	48.00	72.00	48.00	72.00
2	48.00	72.00	48.00	72.00
3	48.00	72.00	48.00	72.00

ZONE	H-1 MIN	H-1 MAX	H-2 MIN	H-2 MAX
1	2.00	100.00	2.00	100.00
2	2.00	100.00	2.00	100.00
3	2.00	100.00	2.00	100.00

ZONE	SPA-1 INC	SPA-2 INC	H-1 INC	H-2 INC
1	12.00	12.00	25	25
2	12.00	12.00	25	25
3	12.00	12.00	25	25

SUMMARY OF ZONE RECTANGULAR GRIDS  
USED IN THE OPTIMIZATION

ZONE NO	MAX NO OF ROWS	MAX NO OF COLS	MAX NO OF FILES
1	10	14	140
2	10	14	140
3	10	14	140

MAX NO OF FILES IN FOUNDATION = 420

MIN PERCENT DELETE HAS BEEN INCREASED

FORM =

614

NUMBER OF OPTIMIZATION VARIABLES = 6

(Continued)

Table VI.13 (Continued)

INITIAL SPACINGS ARE USED FOR  
OPTIMUM BATTER SLOPES CALCULATION

## SPACINGS FOR THIS OPTIMIZATION PASS

ZONE	SPA-1	SPA-2
1	.72000E+02	.72000E+02
2	.72000E+02	.72000E+02
3	.72000E+02	.72000E+02

NF	AXIAL PLF	BENDING PLF	WEIGHTED PLF	NUMBER OF PILES IN ZONE		
				1	2	3
0	.20485E+03	25958E+03	28007E+04	70	66	70
1	.19910E+03	.29964E+03	.31955E+04	70	66	70
2	.19811E+03	.32434E+03	.34416E+04	70	66	70
3	.19833E+03	.30971E+03	.32955E+04	70	66	70
4	.19837E+03	.32465E+03	.34448E+04	70	66	70
5	.19810E+03	.32452E+03	.34433E+04	70	66	70
6	.19909E+03	.29966E+03	.31957E+04	70	66	70
7	.20687E+03	.20143E+03	.22212E+04	70	66	70
8	.20453E+03	.25757E+03	.27802E+04	70	66	70
9	.20466E+03	.25122E+03	.27168E+04	70	66	70
10	.20396E+03	.21100E+03	.23140E+04	70	66	70
11	.19918E+03	.28780E+03	.30772E+04	70	66	70
12	.19897E+03	.29212E+03	.31202E+04	70	66	70
13	.19902E+03	.29134E+03	.31125E+04	70	66	70
14	.19899E+03	.29171E+03	.31161E+04	70	66	70
15	.19899E+03	.29203E+03	.31193E+04	70	66	70
16	.19922E+03	.32621E+03	.34613E+04	70	66	70
17	.19920E+03	.32687E+03	.34679E+04	70	66	70
18	.19925E+03	.32547E+03	.34540E+04	70	66	70
19	.19863E+03	.30650E+03	.32636E+04	70	66	70
20	.19926E+03	.32515E+03	.34507E+04	70	66	70
21	.19927E+03	.32493E+03	.34486E+04	70	66	70
22	.19926E+03	.32537E+03	.34529E+04	70	66	70
23	.19916E+03	.31384E+03	.33375E+04	70	66	70
24	.19923E+03	.31228E+03	.33220E+04	70	66	70
25	.19924E+03	.31200E+03	.33192E+04	70	66	70
26	.20106E+03	.32286E+03	.34297E+04	70	66	70
27	.19937E+03	.35316E+03	.37310E+04	70	66	70
28	.19981E+03	.34429E+03	.36427E+04	70	66	70
29	.19622E+03	.34550E+03	.36512E+04	70	66	70
30	.19830E+03	.32349E+03	.34332E+04	70	66	70
31	.19719E+03	.36809E+03	.38781E+04	70	66	70
32	.19934E+03	.35408E+03	.37402E+04	70	66	70
33	.19883E+03	.32076E+03	.34064E+04	70	66	70
34	.20394E+03	.25195E+03	.27235E+04	70	66	70
35	.20405E+03	.24560E+03	.26601E+04	70	66	70

NOTE: THE BALANCE OF THIS CALCULATION AND  
SEVERAL INTERVENING CALCULATIONS  
HAVE BEEN OMITTED.

(Continued)

Table VI. 13 (Continued)

240	20638E+03	17127E+03	19191E+04	70	66	70
241	20600E+03	17860E+03	19920E+04	70	66	70
242	20597E+03	17696E+03	19755E+04	70	66	70
243	20628E+03	17311E+03	19374E+04	70	66	70
244	20598E+03	17707E+03	19767E+04	70	66	70
245	20579E+03	17933E+03	19991E+04	70	66	70
246	20573E+03	18581E+03	20639E+04	70	66	70
247	20573E+03	18565E+03	20623E+04	70	66	70
248	20616E+03	17761E+03	19822E+04	70	66	70
249	20623E+03	18080E+03	20142E+04	70	66	70
250	20642E+03	17111E+03	19175E+04	70	66	70
251	20623E+03	18080E+03	20142E+04	70	66	70
252	20636E+03	17935E+03	19998E+04	70	66	70
253	20649E+03	17118E+03	19183E+04	70	66	70
254	20653E+03	17128E+03	19194E+04	70	66	70
255	20648E+03	17216E+03	19280E+04	70	66	70
256	20642E+03	16908E+03	18972E+04	70	66	70
257	20633E+03	17560E+03	19623E+04	70	66	70
258	20641E+03	16882E+03	18946E+04	70	66	70
259	20653E+03	16724E+03	18789E+04	70	66	70
260	20659E+03	16712E+03	18778E+04	70	66	70
261	20659E+03	16713E+03	18779E+04	70	66	70
262	20655E+03	16775E+03	18840E+04	70	66	70
263	20655E+03	16748E+03	18814E+04	70	66	70
264	20673E+03	17592E+03	19659E+04	70	66	70
265	20664E+03	17144E+03	19211E+04	70	66	70
266	20660E+03	17199E+03	19265E+04	70	66	70
267	20656E+03	17093E+03	19159E+04	70	66	70
268	20652E+03	17105E+03	19170E+04	70	66	70
269	20654E+03	17063E+03	19128E+04	70	66	70
270	20653E+03	17008E+03	19073E+04	70	66	70
271	20651E+03	16918E+03	18983E+04	70	66	70
272	20654E+03	16884E+03	18949E+04	70	66	70
273	20658E+03	16992E+03	19057E+04	70	66	70
274	20661E+03	16977E+03	19043E+04	70	66	70
275	20670E+03	16815E+03	18882E+04	70	66	70
276	20670E+03	16935E+03	19003E+04	70	66	70
277	20669E+03	16806E+03	18873E+04	70	66	70
278	20661E+03	16930E+03	18996E+04	70	66	70
279	20658E+03	16877E+03	18943E+04	70	66	70
280	20658E+03	16879E+03	18945E+04	70	66	70
281	20657E+03	16881E+03	18947E+04	70	66	70
282	20656E+03	16759E+03	18824E+04	70	66	70
283	20653E+03	16655E+03	18721E+04	70	66	70
284	20657E+03	16599E+03	18665E+04	70	66	70
285	20683E+03	17854E+03	19922E+04	70	66	70
286	20690E+03	17644E+03	19713E+04	70	66	70
287	20652E+03	18283E+03	20348E+04	70	66	70
288	20652E+03	18284E+03	20349E+04	70	66	70
289	20658E+03	16768E+03	18834E+04	70	66	70
290	20653E+03	18361E+03	20427E+04	70	66	70

(Continued)

Table VI.13 (Continued)

291	.20651E+03	.18387E+03	.20452E+04	70	66	70
292	.20628E+03	.17474E+03	.19537E+04	70	66	70
293	.20620E+03	.17507E+03	.19569E+04	70	66	70
294	.20658E+03	.16798E+03	.18863E+04	70	66	70
295	.20659E+03	.16852E+03	.18918E+04	70	66	70

MINIMUM WTD PLF SUM = .18814E+04

## OPTIMUM BATTER SLOPES

ZONE	H-1 OPT	H-2 OPT
1	-.28047E+02	.20009E+01
2	-.45167E+01	.23258E+02
3	.20711E+01	-.30718E+02

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.48000E+02	.48000E+02
2	.48000E+02	.48000E+02
3	.48000E+02	.48000E+02

## DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	10	14	140	.591	1
2	10	14	140	.773	1
3	10	14	140	.578	1
1	10	14	140	.591	2
2	10	14	140	.773	2
3	10	14	140	.578	2
1	10	14	98	.944	3
2	10	14	140	1.418	3
3	10	14	98	1.260	3
1	10	14	140	.591	4
2	10	14	140	.773	4
3	10	14	140	.578	4
1	10	14	119	.723	5
2	10	14	119	1.112	5
3	10	14	119	.963	5
1	10	14	140	.591	6
2	10	14	140	.773	6
3	10	14	140	.578	6
1	10	14	130	.629	7

(Continued)

Table VI.13 (Continued)

2	10	14	130	.907	7
3	10	14	130	.709	7
1	10	14	140	.591	8
2	10	14	140	.773	8
3	10	14	140	.578	8
1	10	14	135	.610	9
2	10	14	135	.834	9
3	10	14	135	.636	9
1	10	14	130	.669	10
2	10	14	130	.883	10
3	10	14	130	.648	10
1	10	14	126	.686	11
2	10	14	126	.942	11
3	10	14	126	.706	11
1	10	14	130	.669	12
2	10	14	130	.883	12
3	10	14	130	.648	12
1	10	14	128	.677	13
2	10	14	128	.912	13
3	10	14	128	.676	13
1	10	14	126	.698	14
2	10	14	126	.934	14
3	10	14	126	.686	14
1	10	14	128	.677	15
2	10	14	128	.912	15
3	10	14	128	.676	15
1	10	14	127	.687	16
2	10	14	127	.922	16
3	10	14	127	.681	16
1	10	14	126	.693	17
2	10	14	126	.938	17
3	10	14	126	.695	17

SWEEP = 17    FAILED BACK-UP TO SWEEP = 16  
 DELETION TERMINATED: PERULT > PDMN.  
 NO. OF PILES = 381  
 EXCESS PLF = 0.  
 MAX. DISPL. = .1582E+00    .3182E-01    .2516E+00  
 PFCOST = 381000.00  
 OBTAINED BY DELETING THE LEAST LOADED PILES.  
 TIME REQUIRED FOR THIS DELETION = 15.644

## DELETING THE MOST LOADED PILES

\*\*\*\*\* FILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	10	14	140	.591	1
2	10	14	140	.773	1
3	10	14	140	.578	1
1	10	14	140	.591	2

(Continued)

Table VI.13 (Continued)

2	10	14	140	.773	2
3	10	14	140	.578	2
1	10	14	98	.690	3
2	10	14	140	.838	3
3	10	14	98	.670	3
1	10	14	140	.591	4
2	10	14	140	.773	4
3	10	14	140	.578	4
1	10	14	119	.633	5
2	10	14	119	.771	5
3	10	14	119	.641	5
1	10	14	102	.746	6
2	10	14	102	.956	6
3	10	14	102	.880	6
1	10	14	119	.633	7
2	10	14	119	.771	7
3	10	14	119	.641	7
1	10	14	111	.697	8
2	10	14	111	.849	8
3	10	14	111	.754	8
1	10	14	119	.633	9
2	10	14	119	.771	9
3	10	14	119	.641	9
1	10	14	115	.661	10
2	10	14	115	.797	10
3	10	14	115	.688	10
1	10	14	111	.703	11
2	10	14	111	.848	11
3	10	14	111	.755	11
1	10	14	115	.661	12
2	10	14	115	.797	12
3	10	14	115	.688	12
1	10	14	113	.682	13
2	10	14	113	.820	13
3	10	14	113	.720	13
1	10	14	111	.704	14
2	10	14	111	.847	14
3	10	14	111	.756	14
1	10	14	113	.682	15
2	10	14	113	.820	15
3	10	14	113	.720	15
1	10	14	112	.693	16
2	10	14	112	.833	16
3	10	14	112	.737	16

SWEEP = 16 FAILED BACK-UP TO SWEEP = 15

DELETION TERMINATED: PERDLT ) PDHN.

NO. OF PILES = 339

EXCESS PLF = 0

MAX. DISPL = 1851E+00 .7415E-01 4731E+00

(Continued)

Table VI.13 (Continued)

OBTAINED BY DELETING THE MOST LOADED PILES.  
TIME REQUIRED FOR THIS DELETION = 9 150

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.48000E+02	.48000E+02
2	.72000E+02	.72000E+02
3	.48000E+02	.60000E+02

DELETING THE LEAST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	10	14	140	.637	1
2	7	10	66	885	1
3	10	11	110	781	1
1	10	14	140	.637	2
2	7	10	66	885	2



NOTE: THE BALANCE OF THIS CALCULATION AND  
SEVERAL INTERVENING CALCULATIONS  
HAVE BEEN OMITTED.

(Continued)

Table VI.13 (Continued)

2	7	10	66	.885	12
3	10	11	110	.781	12
1	10	14	139	.648	13
2	7	10	66	.894	13
3	10	11	109	.780	13
1	10	14	138	.653	14
2	7	10	66	.906	14
3	10	11	108	.793	14

SWEEP = 14 FAILED BACK-UP TO SWEEP = 13  
 DELETION TERMINATED: PERDLT ) PMDN.  
 NO. OF PILES = 314  
 EXCESS PLF = 0.  
 MAX. DISPL. = .1688E+00 .4941E-01 .3222E+00  
 PFCOST = 314000.00  
 OBTAINED BY DELETING THE LEAST LOADED PILES.  
 TIME REQUIRED FOR THIS DELETION = 10.154

## DELETING THE MOST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	10	14	140	.637	1
2	7	10	66	.885	1
3	10	11	110	.781	1
1	10	14	140	.637	2
2	7	10	66	.885	2
3	10	11	110	.781	2
1	10	14	98	.813	3
2	7	10	66	.943	3
3	10	11	110	.800	3
1	10	14	140	.637	4
2	7	10	66	.885	4
3	10	11	110	.781	4
1	10	14	119	.677	5
2	7	10	59	.917	5
3	10	11	94	.940	5
1	10	14	140	.637	6
2	7	10	66	.885	6
3	10	11	110	.781	6
1	10	14	130	.652	7
2	7	10	62	.902	7
3	10	11	102	.838	7
1	10	14	140	.637	8
2	7	10	66	.885	8
3	10	11	110	.781	8
1	10	14	135	.646	9
2	7	10	64	.895	9
3	10	11	106	.806	9
1	10	14	140	.637	10

(Continued)

Table VI.13 (Continued)

2	7	10	66	.885	10
3	10	11	110	.781	10
1	10	14	138	.641	11
2	7	10	65	.890	11
3	10	11	108	.793	11
1	10	14	140	.637	12
2	7	10	66	.885	12
3	10	11	110	.781	12
1	10	14	139	.639	13
2	7	10	66	.888	13
3	10	11	109	.787	13

SWEEP = 13 FAILED BACK-UP TO SWEEP = 12  
 DELETION TERMINATED PERDLT ) PDMM.  
 NO. OF FILES = 316  
 EXCESS PLF = 0  
 MAX. DISPL. = .1661E+00 4965E-01 3243E+00  
 PFCOST = 316000.00  
 OBTAINED BY DELETING THE MOST LOADED FILES.  
 TIME REQUIRED FOR THIS DELETION = 8.979

#### CPU TIME

OPTIMUM BATTER SLOPE PHASE 177.617 SECONDS  
 PILE DELETION PHASE 191.788 SECONDS

#### \*\*\*\*\* OPTIMIZATION RESULTS \*\*\*\*\*

OPTIMUM PILE FOUNDATION COST = 288000.00

ZONE NO.	OPTIMUM SPACINGS		OPTIMUM BATTER SLOPES	
	SPA-1	SPA-2	H-1	H-2
1	.48000E+02	.48000E+02	- 28047E+02	20009E+01
2	.72000E+02	72000E+02	- 45167E+01	23258E+02
3	.48000E+02	.48000E+02	20711E+01	- 30718E+02

#### PLACEMENT OF PILES IN ZONES

PILES WERE DELETED FROM ZONE 1  
 AT GRID PT I , J  
 1 5

(Continued)

Table VI.13 (Continued)

1	7
1	9
1	11
1	13
1	14
2	7
2	9
2	11
2	13
2	14
3	9
3	11
3	13
3	14
4	9
4	11
4	13
5	11
5	13
6	11
6	13
7	13
8	13

ZONE 1 HAS 10 ROWS, 14 COLS, 116 PILES WITH 24 DELETED.

PILES WERE DELETED FROM ZONE 2

AT GRID PT I , J

1	5
1	6
1	7
1	8
1	9
1	10
3	7
3	8
3	9
3	10
5	9
5	10
7	9
7	10

ZONE 2 HAS 7 ROWS, 10 COLS, 56 PILES WITH 14 DELETED.

PILES WERE DELETED FROM ZONE 3

AT GRID PT I , J

1	10
1	12

(Continued)

Table VI.13 (Continued)

1	14
2	10
2	12
2	14
3	12
3	14
4	12
4	14
5	14
6	2
6	14
7	2
7	14
8	2
8	4
9	2
9	4
9	13
10	2
10	4
10	6
10	13

ZONE 3 HAS 10 ROWS, 14 COLS, 116 PILES WITH 74 DELETED.

TOTAL NUMBER OF PILES = 288

SOIL CONDITION NO 1  
STIFFNESS MATRIX S

4116E+05	6028E-03	2021E+05	-.7439E+07	.1561E+07	.1578E+08
.6028E-03	2430E+05	.1694E+04	-.3070E+06	.0582E+05	.5033E+06
2021E+05	-.1694E+04	.1377E+06	-.5361E+08	-.2193E+07	.7353E+07
-.7439E+07	.3070E+06	-.5361E+08	.2562E+11	.3995E+09	-.3466E+10
.1561E+07	.0582E+05	-.2193E+07	-.3995E+09	.2899E+11	.3781E+09
.1578E+08	.5033E+06	.7353E+07	-.3466E+10	.3781E+09	.1213E+11

FLEXIBILITY MATRIX F

5157E-04	5315E-06	-.9425E-05	-.1361E-07	-.2828E-08	.6519E-07
5315E-06	4157E-04	.3751E-05	.8187E-08	.2757E-09	-.2359E-08
-.9425E-05	.3751E-05	.4176E-04	.8630E-07	.4697E-08	.1131E-07
-.1361E-07	.8187E-08	.8630E-07	.2197E-09	.9905E-11	.2751E-10
-.2828E-08	.2757E-09	.4697E-08	.9905E-11	.3511E-10	.2556E-11
-.6519E-07	.2359E-08	.1131E-07	.2751E-10	.2556E-11	.1683E-09

(Continued)

Table VI.13 (Concluded)

RESULTS FOR SOIL CONDITION NO. 1

LOAD CASE	PILE CAP DISPLACEMENTS						
	D1	D2	D3	D4	D5	D6	DMAX
1	.563E-01	.315E-01	.409E+00	.273E-03	.365E-04	.188E-04	.442E+00
2	.168E+00	-.322E-01	.624E-01	-.890E-04	-.892E-04	-.367E-04	.221E+00
3	.128E+00	.156E-01	.196E+00	.111E-03	-.746E-04	-.112E-04	.283E+00
4	.123E+00	-.242E-01	.169E+00	-.171E-04	-.779E-04	-.228E-04	.262E+00
5	.182E+00	-.399E-01	.248E-01	-.128E-03	-.932E-04	-.427E-04	.218E+00
6	.119E+00	-.287E-01	.173E+00	-.282E-04	-.776E-04	-.232E-04	.264E+00
7	.175E+00	.726E-02	.854E-01	.374E-04	-.864E-04	-.256E-04	.231E+00
8	.152E+00	.125E-01	.150E+00	.109E-03	-.972E-04	-.150E-04	.271E+00

FOR SOIL CONDITION NO. 1 SUM OF PLF = .22633E+03

PILE FOUNDATION COST = 288000.00

ARRAY A(NMAX) CONTAINED 231 WORDS.

### Example No. 5 - Abutment Monolith Foundation

Program PILEOPT is used to obtain a pile layout for an abutment monolith in this example. The loads and overall dimensions came from the design of the south abutment D-6 of the John H. Overton Lock and Dam. A sketch of the abutment monolith is shown in Fig. VI.8. The monolith is supported by HP 14x73 steel piles. A subgrade modulus of  $0.01 \text{ kip/in}^3$  is used to represent the soil. The six load cases considered in the design are given in Table VI.14.

Table VI.14 Design Loads for Abutment Monolith

Load Case	Q1 (kips)	Q2 (kips)	Q3 (kips)	Q4 (in-kips)	Q5 (in-kips)	Q6 (in-kips)	Overstress Factor
1	566	95	7,876	90,264	-2,493,696	23,352	1.33
2	620	468	8,974	22,416	-2,706,660	129,540	1.33
3	277	2,485	5,464	327,036	-1,692,696	740,340	1.06
4	277	2,485	6,575	255,984	-2,025,576	740,340	1.06
5	411	2,519	6,120	354,720	-1,918,548	713,772	1.06
6	411	2,519	7,231	283,668	-2,251,428	713,772	1.06

The pile foundation is considered as a single zone. The zone parameters are selected so that the design obtained by PILEOPT could be very similar to the actual design. The values of the zone parameters are listed in Table VI.15 for this problem.

The maximum number of piles in the foundation corresponds to the minimum spacings. With the minimum spacings there are 13 rows in the  $U_1$ -direction and 10 columns in the  $U_2$ -direction in the grid for a maximum number of 130 piles in the foundation. During the Phase I calculation, there is a 11x9 grid of 99 piles for the optimum batter slope determination. The piles

Fig. VI.8 Abutment Monolith

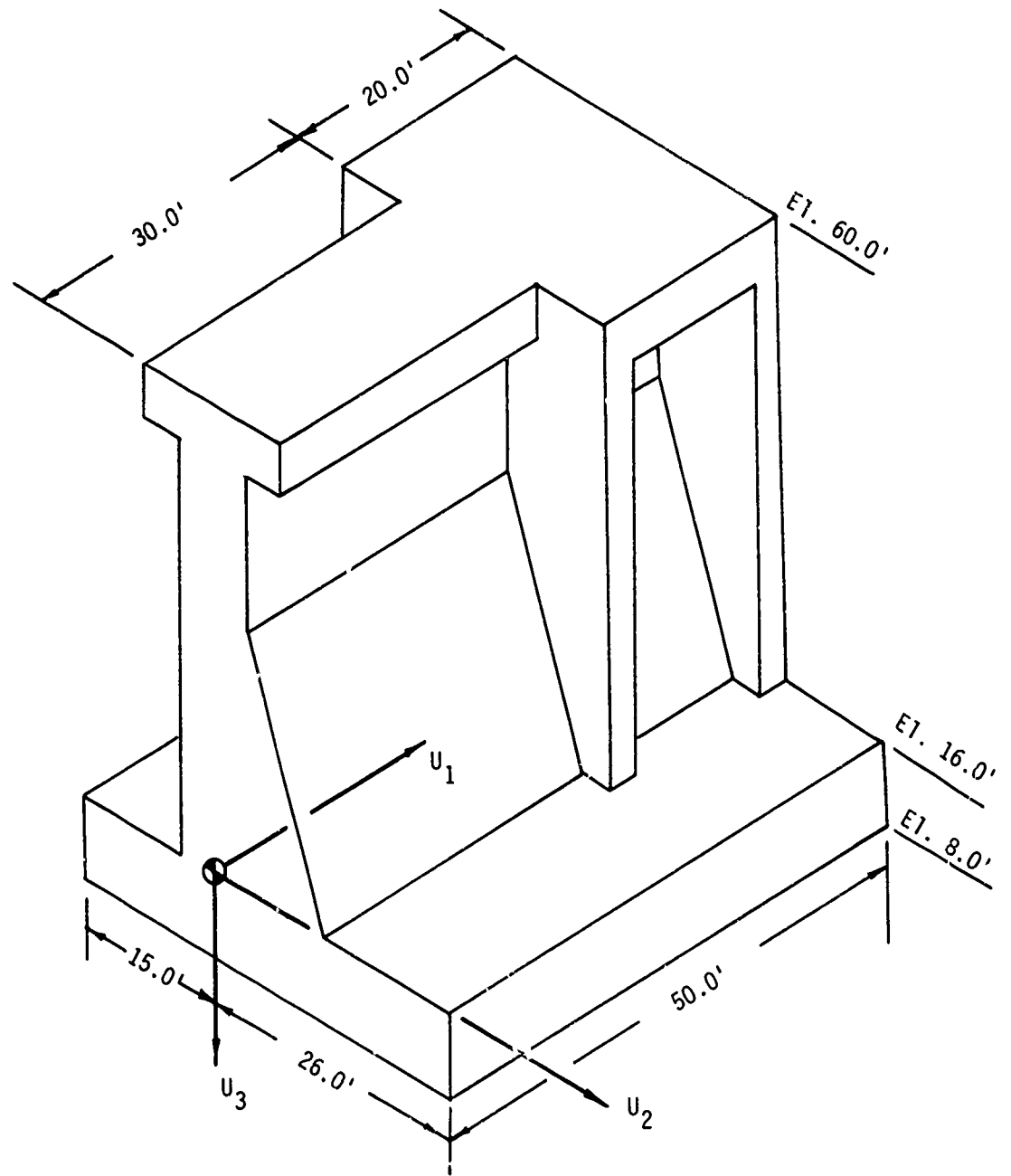


Table VI.15 User Selected Zone Parameters  
for Abutment Monolith

Parameter	Value
ZLN-1	600 in.
ZLN-2	400 in.
BOR-1	0 in.
BOR-2	30 in.
BOR-3	0 in.
BOR-4	30 in.
ALFZN	0°
ALFBT	90°
IFLIP	0
IRC	1
NPB1	1
NPB2	1
SPA-1 MIN	42 in.
SPA-1 MAX	66 in.
SPA-2 MIN	42 in.
SPA-2 MAX	66 in.
H-1 MIN	2:1
H-1 MAX	100:1
H-2 MIN	2:1
H-2 MAX	100:1
SPA-1 INC	6 in.
SPA-2 INC	6 in.
SPA-1 INITIAL	54 in.
SPA-2 INITIAL	50 in.

can be battered either upstream (negative  $U_1$ -direction) or downstream.

The input data for program PILEOPT is given in Table VI.16.

Program PILEOPT produced the pile layout in Fig. V.9 for this abutment monolith. There are 41 piles battered downstream in the  $U_2$ -direction ( $H = 2.08$ ) and 35 piles battered upstream ( $H = -2.01$ ). The layout obtained requires a total of 76 piles to support the abutment monolith.

The actual design of the foundation contained 88 piles to support the monolith.  
Part of the output from PILEOPT for this example is given in Table VI.17.

Table VI.16 PILEOPT Input Data for Abutment Monolith

```

10
  ABUTMENT MONOLITH D-6 OPTIMIZATION OCT. 10, 1978
0.0,0
10.1,1.6,1
0.01,0.772
1.0,300
1.1,1
1.10
25,25,1
0.001
1.1
2.9E4,734,262,21.5,800
1.075,1,1.5,1,1,1
365.5,789.8,2376,180,65
566,95,7876,90264,-2493696,23352,1.3333
620,468,8974,22416,-2706660,129540,1.3333
277,2485,5464,327036,-1692696,740340,1.06
277,2485,6575,255984,-2025576,740340,1.06
411,2519,6120,254720,-1918548,713772,1.06
411,2519,7231,283668,-2251428,713772,1.06
1,0,0
0,-180,96,0
600,400,0
0,30,0,30
0,0,0,0
54,50,25,-25,90
1,1,1,1
42,66,42,66
2,100,2,100
6,6,0.25,0.25

```

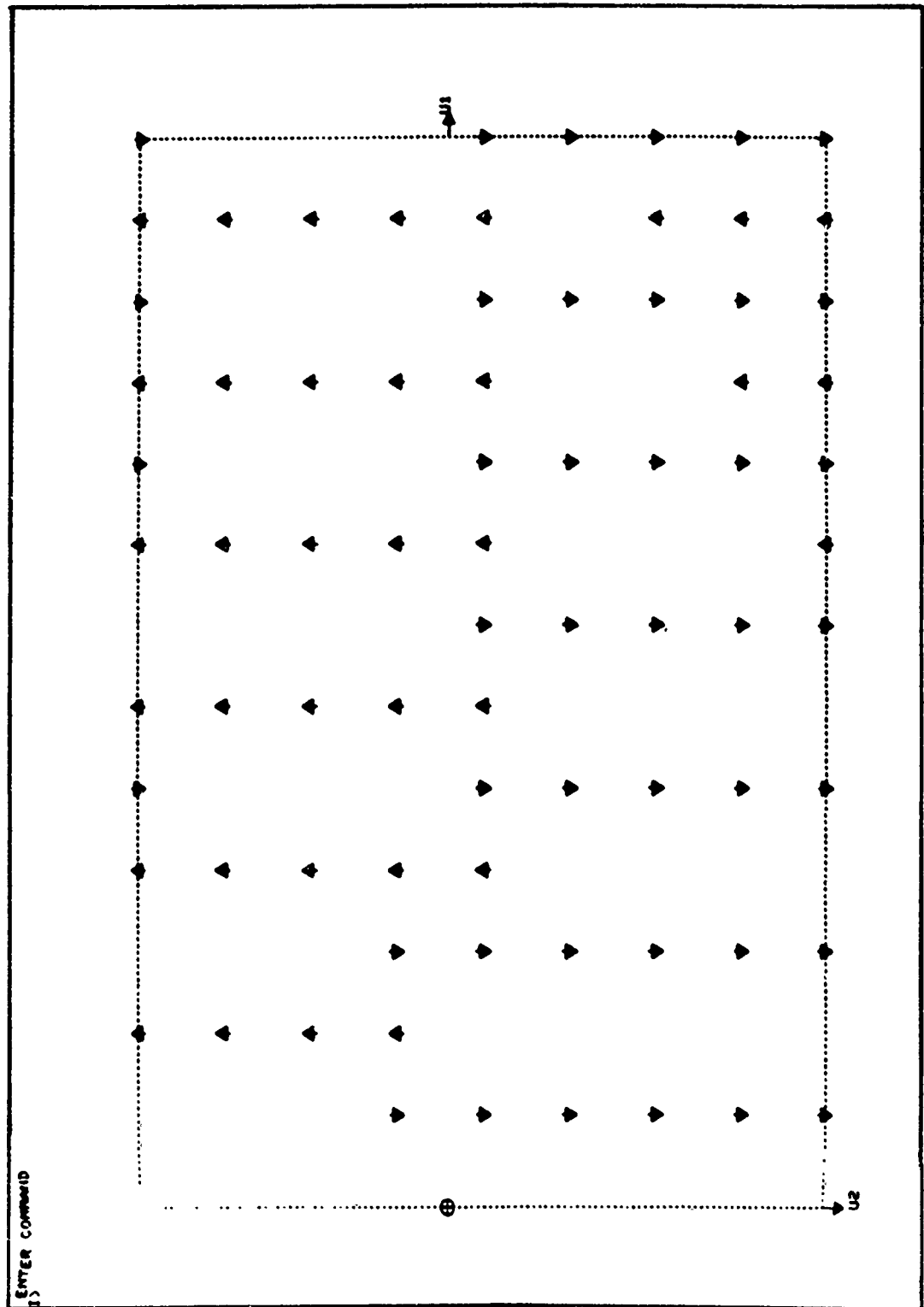


Fig. VI.9 Abutment Monolith Pile Layout

Table VI.17 Output from PILEOPT for Abutment Monolith Problem

\*\*\*\*\* PROGRAM PILEOPT \*\*\*\*\*

ANALYSIS AND OPTIMAL DESIGN OF PILE  
FOUNDATIONS FOR CONCRETE MONOLITHS

PROBLEM HEADING:

ABUTMENT MONOLITH D-6 OPTIMIZATION OCT. 10, 1978

PRINT LEVEL = 10 (BETWEEN 0 AND 99, MORE AND MORE  
INTERMEDIATE RESULTS ARE PRINTED.)

PROGRAM FUNCTION SELECTION = 10  
(0 FOR ANALYSIS, GT 0 FOR  
OPTIMAL DESIGN)

NUMBER OF ZONES = 1  
NUMBER OF PILE GROUPS = 1  
NUMBER OF LOAD CASES = 6

NUMBER OF SOIL COND. = 1

SOIL CONDITION NO. = 1  
SUBGRADE MODULUS = .10000E-01  
BENDING MOMENT FACTOR = .77200E+00

OUTPUT CONTROL OPTIONS:  
(TABLE ? 0-NO, 1-YES)  
IPLG = 0(PILE GEOMETRY)  
IFL = 0(LOCAL FORCES)  
IFG = 0(GLOBAL FORCES)  
ICOST = 1(COST EVALUATIONS)  
INEAT = 0(ENGINEERING ROUNDING)  
NFMAX = 300(MAX NO. OF COST EVALUATIONS)

ALLOWABLE DISPLACEMENT:  
D1 = .1000E+01 D2 = .1000E+01 D3 = .1000E+01

WEIGHT FACTORS FOR OPTIMIZATION  
AXIAL PILE LOAD FACTOR = 1.00

(Continued)

Table VI.17 (Continued)

BENDING PILE LOAD FACTOR = 10.00

PILE DELETION CONTROL PARAMETERS

MAXIMUM NUMBER OF DELETION PASSES = 25

MAXIMUM PERCENT DELETE = 25.000

MINIMUM PERCENT DELETE = 1.000

CONVERGENCE TOLERANCE = .10000E-02

\*\*\*\*\* PILE GROUP DATA \*\*\*\*\*

GROUP NO. 1 PILE COST = 1.00  
 E = .290E+05 IX = 734.0000 IY = 262.0000  
 AREA = 21.5000 LENGTH = 800.0000  
 K1 = 1.075 K2 = 1.000 K3 = 1.500  
 K4 = 1.000 K5 = 1.000 K6 = 1.000

SOIL CONDITION NO. = 1 NH = .10000E-01

LOCAL STIFFNESS MATRIX B

.579E+02	0.	0.	0.	.395E+04	0.
0.	.383E+02	0.	-.213E+04	0.	0.
0.	0.	.779E+03	0.	0.	0.
0.	-.213E+04	0.	.191E+06	0.	0.
.395E+04	0.	0.	0.	.435E+06	0.
0.	0.	0.	0.	0.	.100E+01

ALLOWABLE FORCES AND BENDING MOMENTS

FA = 365.5 FB4 = 789.8 FB5 = 2376.0

CALOW = 180.0 TALOW = 65.0

TABLE OF APPLIED LOADS

LOAD CASE	Q1 M1	Q2 M2	Q3 M3	OVERSTRESS FACTOR
1	.56600E+03 .90264E+05	.95000E+02 -.24937E+07	.78760E+04 .23352E+05	1.333
2	.62000E+03 .22416E+05	.46800E+03 -.27067E+07	.89740E+04 .12954E+06	1.333
3	.27700E+03	.24850E+04	.54640E+04	

(Continued)

Table VI.17 (Continued)

	.32704E+06	-.16927E+07	.74034E+06	1.060
4	.27700E+03	.24850E+04	.65750E+04	
	.25598E+06	-.20256E+07	.74034E+06	1.060
5	.41100E+03	.25190E+04	.61200E+04	
	.25472E+06	-.19185E+07	.71377E+06	1.060
6	.41100E+03	.25190E+04	.72310E+04	
	.28367E+06	-.22514E+07	.71377E+06	1.060

\*\*\*\*\* PILE ZONE DATA \*\*\*\*\*

ZONE NO.	TYPE	REPEAT OF ZONE	FLIP AXIS
1	1	0	0

ZONE NO.	ZONE CORNER COORDINATES			INITIAL RADIUS	ROTATION ALPHA-Z
1	UZC-1	UZC-2	UZC-3		
	0.00	-180.00	96.00	0.00	0.00

ZONE NO.	ZONE DIMENSIONS		ZONE BORDERS			
	LENGTH-1	LENGTH-2	BOR-1	BOR-2	BOR-3	BOR-4
1	600.00	400.00	0.00	30.00	0.00	30.00

ZONE NO.	SHEET PILE LENGTHS			
	SPL-1	SPL-2	SPL-3	SPL-4
1	0.00	0.00	0.00	0.00

ZONE NO.	INITIAL GRID SPACINGS		INITIAL BATTER SLOPES	
	SPA-1	SPA-2	H-1	H-2
1	54.00	50.00	2.50	-2.50

BATTER PATTERN PARAMETERS				
ZONE NO.	DIR. OF CHANGE	PATTERN NUMBERS N1,N2	ANGLE TO BATTER	PILE GROUP
1	1	1, 1	90.00	1

(Continued)

Table VI.17 (Continued)

TABLES OF LIMITING VALUES  
(USED FOR OPTIMIZATION)

ZONE	SPA-1 MIN	SPA-1 MAX	SPA-2 MIN	SPA-2 MAX
1	42.00	66.00	42.00	66.00

ZONE	H-1 MIN	H-1 MAX	H-2 MIN	H-2 MAX
1	2.00	100.00	2.00	100.00

ZONE	SPA-1 INC	SPA-2 INC	H-1 INC	H-2 INC
1	6.00	6.00	.25	.25

SUMMARY OF ZONE RECTANGULAR GRIDS  
USED IN THE OPTIMIZATION

ZONE	MAX NO. NO. OF ROWS	MAX NO. OF COLS	MAX NO. OF PILES
1	13	10	130

MAX NO. OF PILES IN FOUNDATION = 130

MIN. PERCENT DELETE HAS BEEN INCREASED PDMN = .669

NUMBER OF OPTIMIZATION VARIABLES = 2

INITIAL SPACINGS ARE USED FOR  
OPTIMUM BATTER SLOPES CALCULATION

SPACINGS FOR THIS OPTIMIZATION PASS

ZONE	SPA-1	SPA-2
1	.54000E+02	.50000E+02

NF	AXIAL PLF	BENDING PLF	WEIGHTED PLF	NUMBER OF PILES IN ZONE 1
0	.55221E+02	.43511E+02	.49033E+03	99
1	.48866E+02	.94490E+02	.99376E+03	99
2	.48705E+02	.90047E+02	.94917E+03	99
3	.48455E+02	.91439E+02	.96285E+03	99
4	.48469E+02	.92146E+02	.96993E+03	99
5	.48820E+02	.89145E+02	.94027E+03	99
6	.48502E+02	.91839E+02	.96689E+03	99
7	.48557E+02	.92349E+02	.97205E+03	99
8	.48896E+02	.70391E+02	.75279E+03	99
9	.45640E+02	.91610E+02	.96475E+03	99

(Continued)

Table VI.17 (Continued)

10	.67534E+02	.81642E+02	.88395E+03	99
11	.50995E+02	.90870E+02	.95969E+03	99
12	.65600E+02	.77480E+02	.84040E+03	99
13	.50089E+02	.58960E+02	.63969E+03	99
14	.61782E+02	.62785E+02	.68963E+03	99
15	.50278E+02	.75290E+02	.80318E+03	99
16	.49135E+02	.49562E+02	.54475E+03	99
17	.50159E+02	.56313E+02	.61329E+03	99
18	.52294E+02	.55233E+02	.60463E+03	99
19	.54699E+02	.42057E+02	.47526E+03	99
20	.51091E+02	.48477E+02	.53586E+03	99
21	.49719E+02	.51282E+02	.56254E+03	99
22	.51421E+02	.43766E+02	.48908E+03	99
23	.50087E+02	.63943E+02	.68951E+03	99
24	.54826E+02	.61853E+02	.67335E+03	99
25	.54218E+02	.41664E+02	.47086E+03	99
26	.50741E+02	.44442E+02	.49516E+03	99
27	.50035E+02	.45268E+02	.50272E+03	99
28	.53806E+02	.41698E+02	.47079E+03	99
29	.50707E+02	.45852E+02	.50922E+03	99
30	.53952E+02	.42780E+02	.48175E+03	99
31	.54420E+02	.41618E+02	.47060E+03	99

MINIMUM WTD PLF SUM = .47060E+03

OPTIMUM BATTER SLOPES  
 ZONE H-1 OPT H-2 OPT  
 1 .20823E+01 -.20054E+01

SPACINGS FOR THIS DELETION PASS

ZONE SPA-1 SPA-2  
 1 .42000E+02 .42000E+02

DELETING THE LEAST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*  
 ZONE NI NJ PILES AVE PLF ISW  
 1 13 10 130 .529 1  
 1 13 10 98 .730 2  
 1 13 10 80 .935 3  
 1 13 10 98 .730 4  
 1 13 10 86 .858 5  
 1 13 10 98 .730 6

(Continued)

Table VI.17 (Continued)

1	13	10	92	.780	7
1	13	10	87	.843	8
1	13	10	92	.780	9
1	13	10	90	.808	10
1	13	10	88	.818	11
1	13	10	86	.840	12
1	13	10	88	.818	13
1	13	10	87	.835	14
1	13	10	88	.818	15
1	13	10	88	.818	16
1	13	10	88	.818	17
1	13	10	88	.818	25

NO. OF PILES = 88

EXCESS PLF = 0.

MAX. DISPL. = .1956E+00 1821E+00 .2722E+00

PFCOST = 88.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = 3.975

## DELETING THE MOST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	FILES	AVE PLF	ISW
1	13	10	130	.529	1
1	13	10	98	.977	2
1	13	10	130	.529	3
1	13	10	114	.718	4
1	13	10	130	.529	5
1	13	10	122	.608	6
1	13	10	130	.529	7
1	13	10	126	.565	8
1	13	10	123	.596	9
1	13	10	126	.565	10
1	13	10	125	.574	11
1	13	10	124	.584	12
1	13	10	125	.574	13
1	13	10	125	.574	14
1	13	10	125	.574	15
1	13	10	125	.574	25

NO. OF PILES = 125

EXCESS PLF = 0.

MAX. DISPL. = .1363E+00 .1281E+00 .2220E+00

PFCOST = 125.00

OBTAINED BY DELETING THE MOST LOADED PILES

TIME REQUIRED FOR THIS DELETION = 4.190

## SPACINGS FOR THIS DELETION PASS

(Continued)

Table VI.17 (Continued)

ZONE SPA-1 SPA-2  
1 .48000E+02 .42000E+02

## DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	12	10	120	.597	1
1	12	10	110	.650	2
1	12	10	83	.916	3
1	12	10	110	.650	4
1	12	10	97	.770	5
1	12	10	110	.650	6
1	12	10	104	.702	7
1	12	10	98	.742	8
1	12	10	92	.784	9
1	12	10	98	.742	10
1	12	10	95	.762	11
1	12	10	93	.777	12
1	12	10	95	.762	13
1	12	10	94	.766	14
1	12	10	93	.777	15
1	12	10	94	.766	16
1	12	10	94	.766	17
1	12	10	94	.766	18
1	12	10	94	.766	25

NO. OF PILES = 94

EXCESS PLF = 0.

MAX. DISPL. = .2113E+00 .1629E+00 .2055E+00

PFCOST = 94.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = 4.394

## DELETING THE MOST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	12	10	120	.597	1
1	12	10	110	.650	2
1	12	10	83	1.213	3
1	12	10	110	.650	4
1	12	10	97	.860	5
1	12	10	110	.650	6
1	12	10	104	.729	7
1	12	10	110	.650	8
1	12	10	107	.685	9
1	12	10	104	.729	10

(Continued)

Table VI.17 (Continued)

1	12	10	107	.685	11
1	12	10	106	.699	12
1	12	10	107	.685	13
1	12	10	107	.685	14
1	12	10	107	.685	15
1	12	10	107	.685	25

NO. OF PILES = 107  
 EXCESS PLF = 0.  
 MAX. DISPL. = .1800E+00 .1653E+00 .2295E+00  
 PFCOST = 107.00  
 OBTAINED BY DELETING THE MOST LOADED PILES.  
 TIME REQUIRED FOR THIS DELETION = 3.641

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.42000E+02	.48000E+02

DELETING THE LEAST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	13	9	117	.586	1
1	13	9	112	.611	2
1	13	9	84	.914	3
1	13	9	112	.611	4
1	13	9	98	.731	5
1	13	9	86	.835	6
1	13	9	76	.886	7
1	13	9	68	1.054	8
1	13	9	76	.886	9
1	13	9	72	.960	10
1	13	9	76	.886	11
1	13	9	74	.918	12
1	13	9	76	.886	13
1	13	9	75	.902	14
1	13	9	76	.886	15
1	13	9	76	.886	16
1	13	9	76	.886	17
1	13	9	76	.886	25

NO. OF PILES = 76  
 EXCESS PLF = 0.  
 MAX. DISPL. = .2353E+00 .1595E+00 .2418E+00  
 PFCOST = 76.00  
 OBTAINED BY DELETING THE LEAST LOADED PILES.  
 TIME REQUIRED FOR THIS DELETION = 3.599

(Continued)

Table VI.17 (Continued)

## DELETING THE MOST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	13	9	117	.586	1
1	13	9	112	.611	2
1	13	9	84	1.128	3
1	13	9	112	.611	4
1	13	9	98	.829	5
1	13	9	112	.611	6
1	13	9	105	.699	7
1	13	9	112	.611	8
1	13	9	109	.646	9
1	13	9	106	.692	10
1	13	9	103	.748	11
1	13	9	106	.692	12
1	13	9	105	.712	13
1	13	9	106	.692	14
1	13	9	106	.692	15
1	13	9	106	.692	16
1	13	9	106	.692	25

NO. OF PILES = 106

EXCESS PLF = 0.

MAX. DISPL. = .1772E+00 .2176E+00 .2220E+00

PFCOST = 106.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = 3.949

## SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	.42000E+02	.54000E+02

## DELETING THE LEAST LOADED PILES

## \*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	13	8	104	.659	1
1	13	8	104	.659	2
1	13	8	78	.931	3
1	13	8	104	.659	4
1	13	8	91	.758	5
1	13	8	80	.909	6
1	13	8	91	.758	7
1	13	8	86	.818	8
1	13	8	81	.866	9
1	13	8	76	.935	10

(Continued)

Table VI.17 (Continued)

1	13	8	81	.866	11
1	13	8	79	.892	12
1	13	8	81	.866	13
1	13	8	80	.884	14
1	13	8	81	.866	15
1	13	8	81	.866	16
1	13	8	81	.866	17
1	13	8	81	.866	25

NO. OF PILES = 81

EXCESS PLF = 0.

MAX. DISPL. = .2104E+00 .1856E+00 .2435E+00

PFCOST = 81.00

OBTAINED BY DELETING THE LEAST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = 3.218

#### DELETING THE MOST LOADED PILES

#### \*\*\*\*\* PILE DELETION \*\*\*\*

ZONE	NI	NJ	PILES	AVE PLF	ISW
1	13	8	104	.659	1
1	13	8	104	.659	2
1	13	8	78	1.701	3
1	13	8	104	.659	4
1	13	8	91	.887	5
1	13	8	104	.659	6
1	13	8	98	.747	7
1	13	8	104	.659	8
1	13	8	101	.699	9
1	13	8	104	.659	10
1	13	8	103	.671	11
1	13	8	102	.684	12
1	13	8	103	.671	13
1	13	8	103	.671	14
1	13	8	103	.671	15
1	13	8	103	.671	25

NO. OF PILES = 103

EXCESS PLF = 0.

MAX. DISPL. = .1612E+00 .1434E+00 .2290E+00

PFCOST = 103.00

OBTAINED BY DELETING THE MOST LOADED PILES.

TIME REQUIRED FOR THIS DELETION = 3.085

#### CPU TIME

OPTIMUM BATTER SLOPE PHASE 8.027 SECONDS

FILE DELETION PHASE 30.064 SECONDS

(Continued)

Table VI.17 (Continued)

\*\*\*\*\* OPTIMIZATION RESULTS \*\*\*\*\*

OPTIMUM PILE FOUNDATION COST = 76.00

ZONE NO.	OPTIMUM SPACINGS		OPTIMUM BATTER SLOPES	
	SPA-1	SPA-2	H-1	H-2
1	.42000E+02	.48000E+02	.20823E+01	-.20054E+01

PLACEMENT OF PILES IN ZONES

FILES WERE DELETED FROM ZONE 1  
AT GRID PT. I , J

1	1
1	2
1	3
2	5
2	6
2	7
2	8
2	9
3	1
3	2
3	3
4	6
4	7
4	8
4	9
5	2
5	3
5	4
6	6
6	7
6	8
6	9
7	1
7	2
7	3
7	4
8	6
8	7
8	8
9	2

(Continued)

Table VI.17 (Continued)

9	3
9	4
10	6
10	7
11	2
11	3
11	4
12	6
13	2
13	3
13	4

ZONE 1 HAS 13 ROWS, 9 COLS, 76 PILES WITH 41 DELETED.

TOTAL NUMBER OF PILES = 76

SOIL CONDITION NO. 1

STIFFNESS MATRIX S

.2914E+04	.2735E-02	.3310E-03	.7085E-03	.4252E+06	-.8491E+05
.2735E-02	.1497E+05	.1459E+04	-.4221E+06	.1111E+06	.4720E+07
.3310E-03	.1459E+04	.4866E+05	.1229E+07	-.1532E+08	.1111E+06
.7085E-03	-.4221E+06	.1229E+07	.8025E+09	-.4632E+09	-.2168E+09
.4252E+06	-.1111E+06	-.1532E+08	-.4632E+09	.6112E+10	-.6868E+08
-.8491E+05	.4720E+07	.1111E+06	-.2168E+09	-.6868E+08	.1922E+10

FLEXIBILITY MATRIX F

.3611E-03	-.7264E-05	-.3643E-04	-.7069E-08	-.1167E-06	.3092E-07
-.7264E-05	.3133E-03	-.3962E-04	-.4499E-07	-.1052E-06	.7763E-06
-.3643E-04	-.3962E-04	.1064E-03	.1468E-08	.2694E-06	.9898E-07
-.7069E-08	-.4499E-07	-.1468E-08	.1355E-08	.1017E-09	.2667E-09
-.1167E-06	-.1052E-06	.2694E-06	.1017E-09	.8559E-09	.2797E-09
.3092E-07	-.7763E-06	.9898E-07	.2667E-09	.2797E-09	.2462E-08

RESULTS FOR SOIL CONDITION NO. 1

LOAD

PILE CAP DISPLACEMENTS

CASE	I1	I2	I3	I4	I5	I6	IMAX
1	.208E+00	-.461E-01	.144E+00	-.145E-03	-.729E-04	.107E-03	.282E+00
2	.213E+00	.301E-01	.197E+00	-.249E-03	.178E-04	.112E-03	.292E+00
3	.101E+00	.149E+00	.894E-01	.347E-03	-.303E-04	.569E-04	.232E+00
4	.100E+00	.143E+00	.118E+00	.215E-03	-.231E-04	.548E-04	.243E+00
5	.151E+00	.180E+00	.896E-01	.215E-03	.808E-04	-.483E-04	.257E+00
6	.150E+00	.170E+00	.118E+00	.219E-03	-.635E-04	.237E-04	.268E+00

(Continued)

Table VI.17 (Concluded)

FOR SOIL CONDITION NO. 1 SUM OF PLF = .82372E+02

PILE FOUNDATION COST = 76.00

ARRAY A(NMAX) CONTAINED 125 WORDS.

### Example No. 6 - Pump Station Foundation

In this example, the program PILEOPT is used to obtain a pile layout for a pump station foundation. The loads and overall dimensions came from the design of a foundation of a pump station at Teche Vermilion Basins, La. on the Mississippi River. A sketch of the plan view of the pump station showing the walls of the lower chambers is shown in Fig. VI.10. For program PILEOPT, the soil is represented by a subgrade modulus  $n_h = 0.00579$  kip/in<sup>3</sup>. The soil is more exactly represented as three layers of clay, silt, and sand. An analysis of the interaction of the pile and soil-system established that the maximum moment in the pile is 3.73 ft-kip per kip of end shear. This result is included by making the bending moment factor equal to 0.0556 for the calculation of the bending moments in the piles. The pump station is supported by HP 14x73 steel piles that are assumed to bear axial load by soil friction. The six load cases considered in the design are given in Table VI.18.

Table VI.18 Design Loads for Pump Station Foundation

Load Case	Q1 (kips)	Q2 (kips)	Q3 (kips)	Q4 (in-kips)	Q5 (in-kips)	Q6 (in-kips)	Overstress Factor
1	0	0	22,753	0	-8,155,776	0	1.00
2	10,893	0	22,932	0	-10,112,472	0	1.00
3	10,893	0	24,401	0	-10,241,496	0	1.00
4	5,074	0	15,540	0	-6,093,744	0	1.00
5	5,074	0	14,021	0	-5,412,564	0	1.00
6	5,074	0	14,021	-1,817,808	-5,412,564	0	1.00

The pile foundation is considered as twelve zones primarily so that

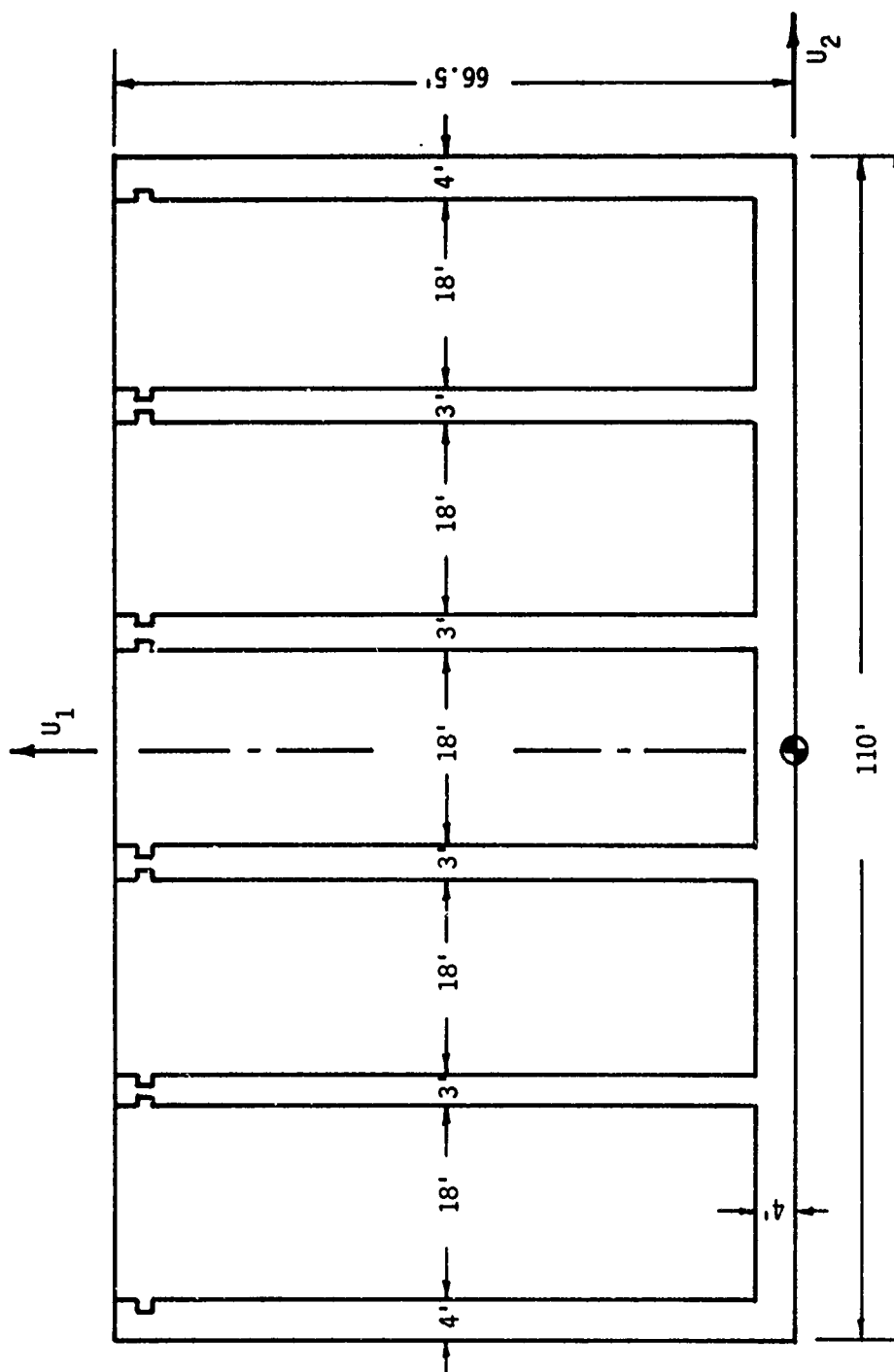


Fig. VI.10 Plan View of Pump Station

the piles can be concentrated under the walls of the lower chambers. The zones and zone parameters are selected so that the design obtained by PILEOPT could be very similar to the actual design. Several zones are duplicates or repeats of others. In particular, Zones - 3, 4, and 5 are repeats of Zone - 1, Zone - 6 is a repeat of Zone -1, Zone - 12 is a repeat of Zone - 7, Zone - 11 is a repeat of Zone - 8, and Zone - 10 is a repeat of Zone - 9. The values of the zone parameters are listed in Table VI.19.

The minimum spacings yield a maximum of 374 piles that could be placed in the foundation. The piles can be battered in the positive and negative  $U_1$ -directions between the limits of 2 and 100. The input for program PILEOPT is given in Table VI.20 for this problem.

The pile layout in Fig. V.11 was produced by PILEOPT for this pump station foundation. This layout requires 198 piles to support the pump station whereas the actual design required a total of 224 piles. Part of the output from PILEOPT for this example is given in Table VI.21.

Table VI.19 User Selected Zone Parameters  
for Pump Station Foundation

Parameter	Zones-1,6	Zones 2,3 4,5	Zones-7,12	Zones-8,11	Zones-9,10
ZLN-1	336 in.	336 in.	336 in.	216 in.	336 in.
ZLN-2	96 in.	180 in.	96 in.	180 in.	180 in.
BOR-1	24 in.	18 in.	24 in.	18 in.	18 in.
BOR-2	18 in.	18 in.	18 in.	18 in.	18 in.
BOR-3	24 in.	18 in.	24 in.	18 in.	18 in.
BOR-4	18 in.	18 in.	18 in.	18 in.	18 in.
ALFZN	0 <sup>0</sup>	0 <sup>0</sup>	0 <sup>0</sup>	0 <sup>0</sup>	0 <sup>0</sup>
ALFBT	0 <sup>0</sup>	0 <sup>0</sup>	0 <sup>0</sup>	0 <sup>0</sup>	0 <sup>0</sup>
IFLIP	0,1	0,0,1,1	0,1	0,1	0,1
IRC	2	2	2	2	2
NPB1	1	1	1	1	1
NPB2	2	2	0	0	0
SPA-1 MIN	48 in.	36 in.	48 in.	48 in.	48 in.
SPA-1 MAX	72 in.	72 in.	72 in.	72 in.	72 in.
SPA-2 MIN	24 in.	36 in.	24 in.	36 in.	36 in.
SPA-2 MAX	54 in.	54 in.	54 in.	54 in.	54 in.
H-1 MIN	2:1	2:1	2:1	2:1	2:1
H-1 MAX	100:1	100:1	100:1	100:1	100:1
H-2 MIN	2:1	2:1	2:1	2:1	2:1
H-2 MAX	100:1	100:1	2:1	2:1	2:1
SPA-1 INC	6 in.	6 in.	6 in.	6 in.	6 in.
SPA-2 INC	6 in.	6 in.	6 in.	6 in.	6 in.
SPA-1 INITIAL	48 in.	48 in.	48 in.	48 in.	48 in.
SPA-2 INITIAL	24 in.	36 in.	24 in.	36 in.	36 in.

Table VI.20 Input Data for Pump Station Foundation Problem

```

10
  PUMP STATION FOUNDATION 10-28-78
0,0,0
1,12,1,6,1
.00579,0.0556
1,0,500
1,1,1
1,10
40,30,1
1,1000
3E4,734,262,21.5,786
.4107, 5,0,0,0,0
200,1200,1200,200,80
0,0,22753,0,-8155776,0,1
10893,0,22932,0,-10112472,0,1.0
10893,0,24401,0,-10241496,0,1.0
5074,0,15540,0,-6093744,0,1
5074,0,14021,0,-5412564,0,1
5074,0,14021,-1817808,-5412564,0,1
1,0,0
18,-660,0,0
336,96,0
24,18,24,18
0,0,0,0
48,24,2,-2,0
1,2,1,1
48,72,24,54
2,100,2,100
6,6,.25,.25
1,0,0
18,-468,0,0
336,180,0
18,18,18,18
0,0,0,0
48,36,-2,2,0
1,2,1,2
36,72,36,54
2,100,2,100
6,6,.25,.25
1,2,0
18,-216,0,0
1,2,1
18,36,0,0
1,2,1
18,288,0,0
1,1,1
18,564,0,0
1,0,0

```

(Continued)

Table VI.20 (Continued)

378, -660, 0, 0  
 336, 96, 0  
 24, 18, 24, 18  
 0, 0, 0, 0  
 48, 24, 2, 2, 0  
 1, 2, 1, 0  
 48, 72, 24, 54  
 2, 100, 2, 2  
 6, 6, 0.25, 0.25  
 1, 0, 0  
 378, -468, 0, 0  
 216, 180, 0  
 18, 18, 18, 18  
 0, 0, 0, 0  
 48, 36, 2, 2, 0  
 1, 2, 1, 0  
 48, 72, 36, 54  
 2, 100, 2, 2  
 6, 6, .25, .25  
 1, 0, 0  
 378, -216, 0, 0  
 336, 180, 0  
 18, 18, 18, 18  
 0, 0, 0, 0  
 48, 36, 2, 2, 0  
 1, 2, 1, 0  
 48, 72, 36, 54  
 2, 100, 2, 2  
 6, 6, .25, .25  
 1, 9, 1  
 378, 36, 0, 0  
 1, 8, 1  
 378, 288, 0, 0  
 1, 7, 1  
 378, 564, 0, 0

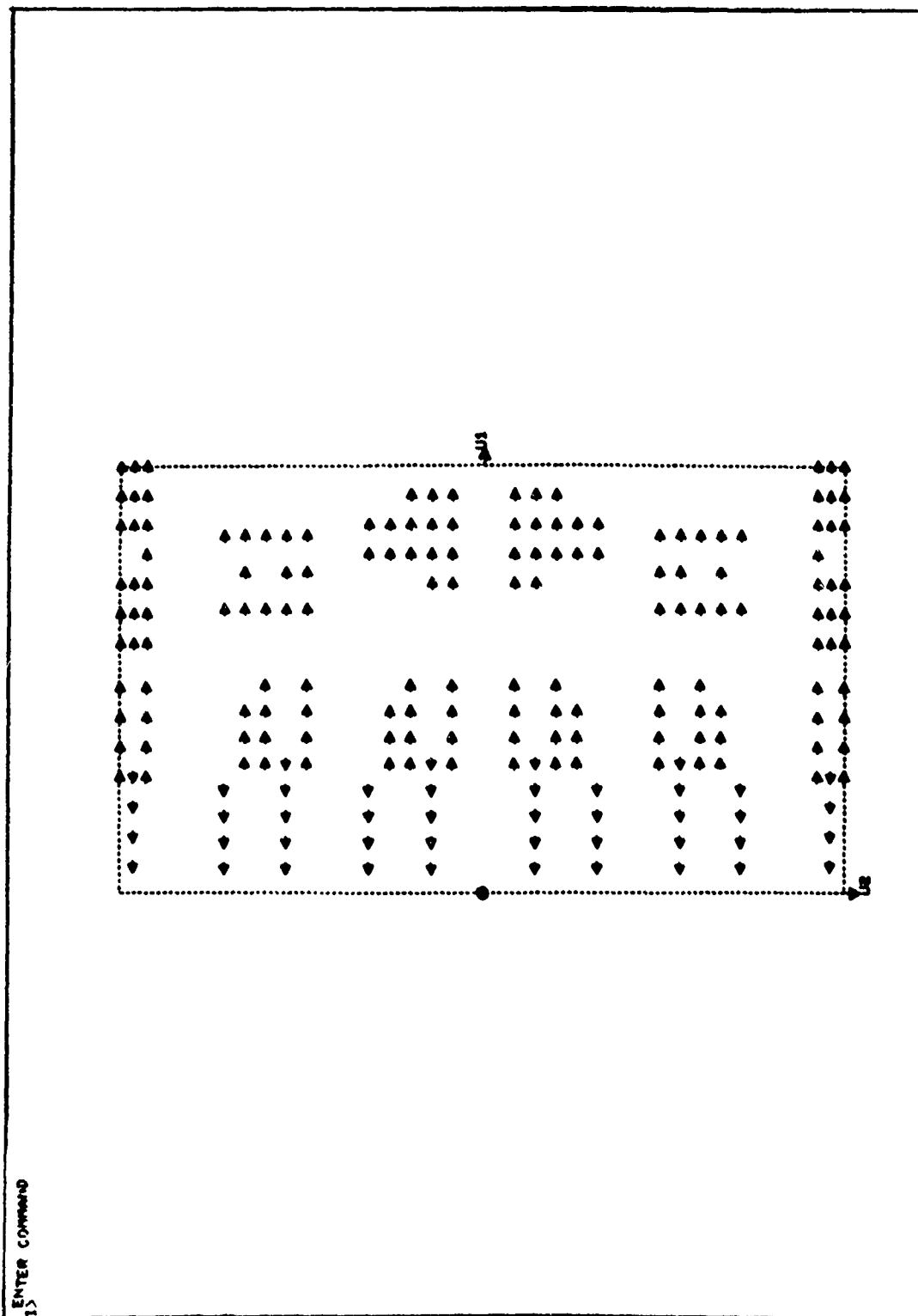


Fig. VI.11 Pile Layout for Pump Station Foundation

Table VI.21 Output from PILEOPT for Pump Station Foundation Problem

```

1 ***** PROGRAM PILEOPT *****
ANALYSIS AND OPTIMAL DESIGN OF PILE
FOUNDATIONS FOR CONCRETE MONOLITHS
PROBLEM HEADING
PUMP STATION FOUNDATION 10-28-78

PRINT LEVEL = 10 (BETWEEN 0 AND 99. MORE AND MORE
INTERMEDIATE RESULTS ARE PRINTED)

PROGRAM FUNCTION SELECTION = 1
(O FOR ANALYSIS, GT 0 FOR
OPTIMAL DESIGN)
NUMBER OF ZONES = 12
NUMBER OF PILE GROUPS = 1
NUMBER OF LOAD CASES = 6
NUMBER OF SOIL COND = 1

SOIL CONDITION NO = 1
SUBGRADE MODULUS = 57900E-02
BENDING MOMENT FACTOR = 55600E-01

OUTPUT CONTROL OPTIONS:
(TABLE ? 0-NO, 1-YES)
IFLG = 0(PILE GEOMETRY)
IFL = 0(LOCAL FORCES)
IFG = 0(GLOBAL FORCES)
ICOST = 1(COST EVALUATIONS)
INEAT = 0(ENGINEERING ROUNDING)
NFMAX = 500(MAX NO. OF COST EVALUATIONS)

ALLOWABLE DISPLACEMENT
D1 = 1000E+01 D2 = 1000E+01 D3 = 1000E+01

WEIGHT FACTORS FOR OPTIMIZATION
AXIAL PILE LOAD FACTOR = 1.00
BENDING PILE LOAD FACTOR = 10.00

PILE DELETION CONTROL PARAMETERS
MAXIMUM NUMBER OF DELETION PASSES = 40

```

(Continued)

Table VI.21 (Continued)

MAXIMUM PERCENT DELETE = 30.000  
MINIMUM PERCENT DELETE = 1.000

\*\*\*\*\* PILE GROUP DATA \*\*\*\*\*

GROUP NO. 1 PILE COST = 1000.00  
E = 300E+05 IX = 734.0000 IY = 262.0000  
AREA = 21.5000 LENGTH = 786.0000  
K1 = 411 K2 = 500 K3 = 0.000  
K4 = 0.000 K5 = 0.000 K6 = 0.000

SOIL CONDITION NO = 1 NH = 57900E-02

LOCAL STIFFNESS MATRIX B

162E+02	0	107E+02	0	0	0	0	0
0	0	107E+02	0	0	0	0	0
0	0	0	410E+03	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

ALLOWABLE FORCES AND BENDING MOMENTS  
FA = 200.0 FB4 = 1200.0 FB5 = 1200.0  
CALOW = 200.0 TALOW = 80.0

LOAD CASE	TABLE OF APPLIED LOADS			OVERSTRESS FACTOR
	Q1 M1	Q2 M2	Q3 M3	
1	0	0	22753E+05	1.000
2	10893E+05	0	22932E+05	1.000
3	10893E+05	0	24401E+05	1.000
4	50740E+04	0	15540E+05	1.000
5	50740E+04	0	14021E+05	1.000
6	50740E+04	0	14021E+05	1.000

(Continued)

Table VI.21 (Continued)

*****			PILE ZONE DATA			*****		
ZONE NO	TYPE	REPEAT OF ZONE	FLIP AXIS					
1	1	0	0					
2	1	0	0					
3	1	2	0					
4	1	2	1					
5	1	2	1					
6	1	1	1					
7	1	0	0					
8	1	0	0					
9	1	0	0					
10	1	9	1					
11	1	8	1					
12	1	7	1					

ZONE NO	ZONE CORNER COORDINATES			INITIAL RADIUS	ROTATION ALPHA-2
	U2C-1	U2C-2	U2C-3		
1	18 00	-660 00	0 00	0 00	0 00
2	18 00	-468 00	0 00	0 00	0 00
3	18 00	-216 00	0 00	0 00	0 00
4	18 00	36 00	0 00	0 00	0 00
5	18 00	288 00	0 00	0 00	0 00
6	18 00	564 00	0 00	0 00	0 00
7	378 00	-660 00	0 00	0 00	0 00
8	378 00	-468 00	0 00	0 00	0 00
9	378 00	-216 00	0 00	0 00	0 00
10	378 00	36 00	0 00	0 00	0 00
11	378 00	288 00	0 00	0 00	0 00
12	378 00	564 00	0 00	0 00	0 00

ZONE NO	ZONE DIMENSIONS			ZONE BORDERS			
	LENGTH-1	LENGTH-2		BOR-1	BOR-2	BOR-3	BOR-4
1	336 00	96 00	24 00	18 00	18 00	24 00	18 00
2	336 00	180 00	18 00	18 00	18 00	18 00	18 00
3	336 00	180 00	18 00	18 00	18 00	18 00	18 00
4	336 00	180 00	18 00	18 00	18 00	18 00	18 00
5	336 00	180 00	18 00	18 00	18 00	18 00	18 00
6	336 00	96 00	24 00	18 00	18 00	24 00	18 00
7	336 00	96 00	24 00	18 00	18 00	24 00	18 00
8	216 00	180 00	18 00	18 00	18 00	18 00	18 00
9	336 00	180 00	18 00	18 00	18 00	18 00	18 00
10	336 00	180 00	18 00	18 00	18 00	18 00	18 00
11	216 00	180 00	18 00	18 00	18 00	18 00	18 00
12	336 00	96 00	24 00	18 00	18 00	24 00	18 00

ZONE NO	SHEET PILE LENGTHS			SPL-4
	SPL-1	SPL-2	SPL-3	
1	0 00	0 00	0 00	0 00
2	0 00	0 00	0 00	0 00

(Continued)

Table VI.21 (Continued)

ZONE NO	INITIAL GRID SPACINGS	INITIAL BATTER SLOPES
3	0.00	0.00
4	0.00	0.00
5	0.00	0.00
6	0.00	0.00
7	0.00	0.00
8	0.00	0.00
9	0.00	0.00
10	0.00	0.00
11	0.00	0.00
12	0.00	0.00

ZONE NO	INITIAL GRID SPACINGS	INITIAL BATTER SLOPES
1	SPA-1 48.00	H-1 2.00
2	SPA-2 48.00	H-2 -2.00
3	48.00	2.00
4	48.00	-2.00
5	48.00	2.00
6	48.00	-2.00
7	48.00	2.00
8	48.00	2.00
9	48.00	2.00
10	48.00	2.00
11	48.00	2.00
12	48.00	2.00

ZONE NO	DIR OF CHANGE	BATTER PATTERN PARAMETERS	PILE GROUP
1	2	NUMBERS N1, N2 1, 1	1
2	2	ANGLE TO BATTER 0.00	1
3	2	1, 2	1
4	2	1, 2	1
5	2	1, 2	1
6	2	1, 1	1
7	2	1, 0	1
8	2	1, 0	1
9	2	1, 0	1
10	2	1, 0	1
11	2	1, 0	1
12	2	1, 0	1

TABLES OF LIMITING VALUES  
(USED FOR OPTIMIZATION)

ZONE	SPA-1 MIN	SPA-1 MAX	SPA-2 MIN	SPA-2 MAX
1	48.00	72.00	24.00	54.00
2	36.00	72.00	36.00	54.00
3	36.00	72.00	36.00	54.00
4	36.00	72.00	36.00	54.00

(Continued)

Table VI.21 (Continued)

ZONE	H-1 MIN	H-1 MAX	H-2 MIN	H-2 MAX
5	36 00	72 00	36 00	54 00
6	48 00	72 00	24 00	54 00
7	48 00	72 00	24 00	54 00
8	48 00	72 00	36 00	54 00
9	48 00	72 00	36 00	54 00
10	48 00	72 00	36 00	54 00
11	48 00	72 00	36 00	54 00
12	48 00	72 00	24 00	54 00
ZONE	H-1 MIN	H-1 MAX	H-2 MIN	H-2 MAX
1	2 00	100 00	2 00	100 00
2	2 00	100 00	2 00	100 00
3	2 00	100 00	2 00	100 00
4	2 00	100 00	2 00	100 00
5	2 00	100 00	2 00	100 00
6	2 00	100 00	2 00	2 00
7	2 00	100 00	2 00	2 00
8	2 00	100 00	2 00	2 00
9	2 00	100 00	2 00	2 00
10	2 00	100 00	2 00	2 00
11	2 00	100 00	2 00	2 00
12	2 00	100 00	2 00	2 00
ZONE	SPA-1 INC	SPA-2 INC	H-1 INC	H-2 INC
1	6 00	6 00	25	25
2	6 00	6 00	25	25
3	6 00	6 00	25	25
4	6 00	6 00	25	25
5	6 00	6 00	25	25
6	6 00	6 00	25	25
7	6 00	6 00	25	25
8	6 00	6 00	25	25
9	6 00	6 00	25	25
10	6 00	6 00	25	25
11	6 00	6 00	25	25
12	6 00	6 00	25	25

SUMMARY OF ZONE RECTANGULAR GRIDS  
USED IN THE OPTIMIZATION

ZONE NO	MAX NO OF ROWS	MAX NO OF COLS	MAX NO OF PILES
1	7	3	21
2	9	5	45
3	9	5	45
4	9	5	45
5	9	5	45
6	7	3	21
7	7	3	21
8	4	5	20
9	7	5	35
10	7	5	35
11	4	5	20
12	7	3	21

(Continued)

Table VI.21 (Continued)

MAX NO OF PILES IN FOUNDATION = 374  
 MIN PERCENT DELETE HAS BEEN INCREASED PDMM = 2 122  
 NUMER OF OPTIMIZATION VARIABLES = 7

INITIAL SPACINGS ARE USED FOR  
 OPTIMUM BATTER SLOPES CALCULATION

SPACINGS FOR THIS OPTIMIZATION PASS

ZONE	SPA-1	SPA-2
1	48000E+02	24000E+02
2	48000E+02	36000E+02
3	48000E+02	36000E+02
4	48000E+02	36000E+02
5	48000E+02	36000E+02
6	48000E+02	24000E+02
7	48000E+02	24000E+02
8	48000E+02	36000E+02
9	48000E+02	36000E+02
10	48000E+02	36000E+02
11	48 30E+02	36000E+02
12	48000E+02	24000E+02

NF	AXIAL PLF	BENDING PLF	WEIGHTED PLF	NUMBER OF PILES IN ZONE					7	8	9	10	11	12
0	18043E+03	77587E+01	25802E+03	1	2	3	4	5	21	21	35	35	35	12
1	15396E+03	35348E+02	50744E+03	21	35	35	35	35	21	21	35	35	35	21
2	15386E+03	35050E+02	50437E+03	21	35	35	35	35	21	21	35	35	35	21
3	14779E+03	35532E+02	50311E+03	21	35	35	35	35	21	21	35	35	35	21
4	14876E+03	36475E+02	51351E+03	21	35	35	35	35	21	21	35	35	35	21
5	15582E+03	35647E+02	51229E+03	21	35	35	35	35	21	21	35	35	35	21
6	15517E+03	35579E+02	51096E+03	21	35	35	35	35	21	21	35	35	35	21
7	15607E+03	36223E+02	51830E+03	21	35	35	35	35	21	21	35	35	35	21
8	18774E+03	16864E+02	35638E+03	21	35	35	35	35	21	21	35	35	35	21
9	13769E+03	16706E+02	35475E+03	21	35	35	35	35	21	21	35	35	35	21
10	18751E+03	16101E+02	34852E+03	21	35	35	35	35	21	21	35	35	35	21
11	17158E+03	15627E+02	32786E+03	21	35	35	35	35	21	21	35	35	35	21
12	17745E+03	12497E+02	30242E+03	21	35	35	35	35	21	21	35	35	35	21
13	17036E+03	17470E+02	34507E+03	21	35	35	35	35	21	21	35	35	35	21
14	14002E+03	39947E+02	53949E+03	21	35	35	35	35	21	21	35	35	35	21
15	14727E+03	37954E+02	52682E+03	21	35	35	35	35	21	21	35	35	35	21
16	19008E+03	20719E+02	39722E+03	21	35	35	35	35	21	21	35	35	35	21
17	19079E+03	20160E+02	39239E+03	21	35	35	35	35	21	21	35	35	35	21
18	17548E+03	22569E+02	40116E+03	21	35	35	35	35	21	21	35	35	35	21
19	17929E+03	24161E+02	42090E+03	21	35	35	35	35	21	21	35	35	35	21
20	20216E+03	20879E+02	41094E+03	21	35	35	35	35	21	21	35	35	35	21
21	20049E+03	20807E+02	40856E+03	21	35	35	35	35	21	21	35	35	35	21
22	20544E+03	22054E+02	42597E+03	21	35	35	35	35	21	21	35	35	35	21
23	14337E+03	39344E+02	53681E+03	21	35	35	35	35	21	21	35	35	35	21

(Continued)

Table VI.21 (Continued)

24	14600E+03	39176E+02	53776E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
25	15173E+03	38729E+02	53902E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
26	16410E+03	36916E+02	53326E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
27	16260E+03	35766E+02	52026E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
28	16290E+03	34866E+02	51156E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
29	16224E+03	34519E+02	50743E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
30	19521E+03	26419E+02	45939E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
31	18138E+03	82313E+01	26369E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
32	18064E+03	90691E+01	27133E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
33	17968E+03	13029E+02	30996E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
34	17685E+03	10738E+02	28624E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
35	18479E+03	83190E+01	26798E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
36	18462E+03	81768E+01	26639E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
37	18778E+03	95778E+01	28356E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
38	16939E+03	32204E+02	49143E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
39	18053E+03	31138E+02	49191E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
40	18491E+03	30752E+02	47243E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
41	20160E+03	26100E+02	46259E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
42	19436E+03	23512E+02	42948E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
43	19316E+03	21655E+02	40970E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
44	18177E+03	18998E+02	37195E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
45	18127E+03	11547E+02	29675E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
46	18230E+03	18706E+02	36936E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
47	18344E+03	18508E+02	36852E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
48	19884E+03	14684E+02	34569E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
49	19746E+03	14006E+02	33752E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
50	19558E+03	13719E+02	33277E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
51	19408E+03	13446E+02	32858E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
52	19124E+03	13001E+02	32125E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
53	18212E+03	11151E+02	29363E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
54	19087E+03	12884E+02	31971E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
55	19089E+03	12838E+02	31927E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
56	19657E+03	10721E+02	30378E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
57	19547E+03	10441E+02	29988E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
58	19454E+03	10319E+02	29773E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
59	19372E+03	10202E+02	29574E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
60	19221E+03	10004E+02	29225E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
61	18920E+03	97962E+01	28717E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
62	19159E+03	98576E+01	29016E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
63	19130E+03	98196E+01	28950E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
64	18622E+03	12260E+02	30881E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
65	18570E+03	11733E+02	30303E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
66	18493E+03	11486E+02	29979E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
67	18433E+03	11256E+02	29689E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
68	18326E+03	10865E+02	29719E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
69	18721E+03	99913E+01	28712E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
70	18326E+03	10893E+02	29219E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
71	18325E+03	10906E+02	29231E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
72	18375E+03	10374E+02	28749E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
73	18779E+03	10455E+02	28835E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
74	18390E+03	10495E+02	28889E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
75	18399E+03	10532E+02	28931E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
76	18418E+03	10598E+02	29015E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
77	18639E+03	10131E+02	28770E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
78	17994E+03	76554E+01	25650E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
79	18050E+03	95500E+01	26600E+03	21	35	35	35	35	35	21	21	20	35	35	20	21

(Continued)

Table VI.21 (Continued)

192	18018E+03	61148E+01	24132E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
193	18093E+03	63478E+01	2441E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
194	17935E+03	60649E+01	2400E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
195	17983E+03	61400E+01	24123E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
196	18003E+03	63363E+01	24339E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
197	18004E+03	63427E+01	24347E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
198	18025E+03	64838E+01	24508E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
199	18166E+03	71951E+01	25361E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
200	18133E+03	71012E+01	25234E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
201	18414E+03	77167E+01	26130E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
202	18327E+03	75253E+01	25852E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
203	17990E+03	64866E+01	24477E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
204	18238E+03	71860E+01	25424E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
205	18239E+03	72069E+01	25445E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
206	18220E+03	70382E+01	25258E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
207	18068E+03	62988E+01	24366E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
208	17920E+03	62468E+01	24167E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
209	17917E+03	60535E+01	23970E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
210	17930E+03	60878E+01	24017E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
211	18317E+03	72027E+01	25520E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
212	17931E+03	60987E+01	24029E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
213	17925E+03	60714E+01	23997E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
214	17938E+03	61367E+01	24075E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
215	17941E+03	63272E+01	24289E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
216	18342E+03	71838E+01	25526E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
217	18197E+03	68337E+01	25031E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
218	18141E+03	66448E+01	24786E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
219	17998E+03	62573E+01	24256E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
220	18146E+03	66691E+01	24816E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
221	18184E+03	69015E+01	25085E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
222	18169E+03	67567E+01	24926E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
223	18167E+03	67404E+01	24908E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
224	18086E+03	65062E+01	24592E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
225	17944E+03	62898E+01	24234E+03	21	35	35	35	35	35	21	21	20	35	35	20	21
226	17943E+03	63001E+01	24243E+03	21	35	35	35	35	35	21	21	20	35	35	20	21

MINIMUM WTD PLF SUM = 24017E+03

OPTIMUM BATTER SLOPES		
ZONE	H-1 OPT	H-2 OPT
1	20401E+01 - 21008E+01	
2	21621E+01	20081E+01
3	21621E+01	20081E+01
4	21621E+01	20081E+01
5	21621E+01	20081E+01
6	20401E+01 - 21008E+01	
7	21265E+01	20000E+01
8	38953E+01	20000E+01
9	86342E+01	20000E+01
10	86342E+01	20000E+01
11	38953E+01	20000E+01
12	21265E+01	20000E+01

(Continued)

Table VI.21 (Continued)

SPACINGS FOR THIS DELETION PASS

ZONE	SPA-1	SPA-2
1	48000E+02	24000E+02
2	36000E+02	36000E+02
3	36000E+02	36000E+02
4	36000E+02	36000E+02
5	36000E+02	36000E+02
6	48000E+02	24000E+02
7	48000E+02	24000E+02
8	48000E+02	36000E+02
9	48000E+02	36000E+02
10	48000E+02	36000E+02
11	48000E+02	36000E+02
12	48000E+02	24000E+02

DELETING THE LEAST LOADED PILES

***** PILE DELETION ****				
ZONE	NI	NJ	PILES AVE	PLF ISM
1	7	3	21	452
2	9	5	45	457
3	9	5	45	457
4	9	5	45	457
5	9	5	45	457
6	7	3	21	452
7	7	3	21	451
8	4	5	20	533
9	7	5	35	517
10	7	5	35	517
11	4	5	20	533
12	7	3	21	451
1	7	3	15	700
2	9	5	32	675
3	9	5	32	675
4	9	5	32	675
5	9	5	32	675
6	7	3	15	700
7	7	3	21	772
8	4	5	15	632
9	7	5	25	522
10	7	5	25	522
11	4	5	15	632
12	7	3	21	772
1	7	3	11	913
2	9	5	23	927
3	9	5	23	927
4	9	5	23	927
5	9	5	23	927
6	7	3	11	913
7	7	3	21	864
8	4	5	11	716

Table VI.21 (Continued)

9	7	5	18	732	3
10	7	5	18	732	3
11	4	5	11	716	3
12	7	3	21	864	3
1	7	3	15	700	4
2	9	5	32	675	4
3	9	5	32	675	4
4	9	5	32	675	4
5	9	5	32	675	4
6	7	3	15	700	4
7	7	3	21	772	4
8	4	5	15	632	4
9	7	5	25	522	4
10	7	5	25	522	4
11	4	5	15	632	4
12	7	3	21	772	4
1	7	3	13	801	5
2	9	5	28	780	5
3	9	5	28	780	5
4	9	5	28	780	5
5	9	5	28	780	5
6	7	3	13	801	5
7	7	3	18	850	5
8	4	5	13	699	5
9	7	5	22	592	5
10	7	5	22	592	5
11	4	5	13	699	5
12	7	3	18	850	5
1	7	3	12	926	6
2	9	5	24	928	6
3	9	5	24	928	6
4	9	5	24	928	6
5	9	5	24	928	6
6	7	3	12	926	6
7	7	3	16	922	6
8	4	5	12	758	6
9	7	5	19	662	6
10	7	5	19	662	6
11	4	5	12	758	6
12	7	3	16	922	6
1	7	3	12	969	7
2	9	5	23	967	7
3	9	5	23	967	7
4	9	5	23	967	7
5	9	5	23	967	7
6	7	3	12	969	7
7	7	3	15	991	7
8	4	5	11	817	7
9	7	5	17	723	7
10	7	5	17	723	7
11	4	5	11	817	7
12	7	3	15	991	7
1	7	3	12	926	8
2	9	5	24	928	8
3	9	5	24	928	8
4	9	5	24	928	8

(Continued)

Table VI.21 (Continued)

5	9	24	928	8
6	7	12	926	8
7	7	16	922	8
8	4	12	758	8
9	7	19	662	8
10	7	19	662	8
11	4	12	758	8
12	7	16	922	8
1	7	12	960	9
2	9	23	959	9
3	9	23	959	9
4	9	23	959	9
5	9	23	959	9
6	7	12	960	9
7	7	15	969	9
8	4	12	796	9
9	7	18	694	9
10	7	18	694	9
11	4	12	796	9
12	7	15	969	9
1	7	12	963	10
2	9	23	961	10
3	9	23	961	10
4	9	23	961	10
5	9	23	961	10
6	7	12	963	10
7	7	15	980	10
8	4	12	806	10
9	7	17	711	10
10	7	17	711	10
11	4	12	806	10
12	7	15	980	10
1	7	12	960	11
2	9	23	959	11
3	9	23	959	11
4	9	23	959	11
5	9	23	959	11
6	7	12	960	11
7	7	15	969	11
8	4	12	796	11
9	7	18	694	11
10	7	18	694	11
11	4	12	796	11
12	7	15	969	11
1	7	12	960	12
2	9	23	959	12
3	9	23	959	12
4	9	23	959	12
5	9	23	959	12
6	7	12	960	12
7	7	15	969	12
8	4	12	796	12
9	7	18	694	12
10	7	18	694	12
11	4	12	796	12
12	7	15	969	12

(Continued)

Table VI.21 (Continued)

1	7	3	12	960	13
2	9	5	23	959	13
3	9	5	23	959	13
4	9	5	23	959	13
5	9	5	23	959	13
6	7	3	12	960	13
7	7	3	15	969	13
8	4	5	12	796	13
9	7	5	18	694	13
10	7	5	18	694	13
11	4	5	12	796	13
12	7	3	15	969	13
1	7	3	12	960	40
2	9	5	23	959	40
3	9	5	23	959	40
4	9	5	23	959	40
5	9	5	23	959	40
6	7	3	12	960	40
7	7	3	15	969	40
8	4	5	12	796	40
9	7	5	18	694	40
10	7	5	18	694	40
11	4	5	12	796	40
12	7	3	15	969	40

NO OF PILES = 206

EXCESS PLF = 0 5357E+00 7378E-01 3926E+00

MAX DISPL = 206000 00

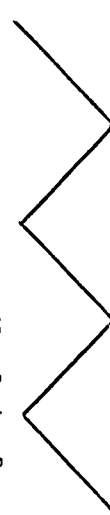
PFCOST = 206000 00

OBTAINED BY DELETING THE LEAST LOADED PILES

TIME REQUIRED FOR THIS DELETION = 8 821

DELETING THE MOST LOADED PILES

**** PILE DELETION ****				
ZONE	NI	NJ	PILES	AVE PLF ISW
1	7	3	21	452 1
2	9	5	45	457 1
3	9	5	45	457 1
4	9	5	45	457 1
5	9	5	45	457 1
6	7	3	21	452 1
7	7	3	21	651 1
8	4	5	20	533 1



NOTE: THE BALANCE OF THIS CALCULATION AND  
SEVERAL INTERVENING CALCULATIONS  
HAVE BEEN OMITTED.

(Continued)

Table VI.21 (Continued)

10 7 4 13 793 40  
 11 4 5 19 756 40  
 12 7 3 20 916 40  
 NO OF PILES = 208  
 EXCESS PLF = 0  
 MAX DISPL = 5216E+00 7835E-01 4638E+00  
 PFCOST = 208000 00  
 OBTAINED BY DELETING THE LEAST LOADED PILES  
 TIME REQUIRED FOR THIS DELETION = 7 749

DELETING THE MOST LOADED PILES

\*\*\*\*\* PILE DELETION \*\*\*\*\*  
 ZONE NI NJ PILES AVE PLF ISW  
 1 7 3 21 492 1  
 2 8 5 40 498 1  
 3 8 5 40 498 1  
 4 8 5 40 498 1  
 5 8 5 40 498 1  
 6 7 3 21 492 1  
 7 7 3 21 709 1  
 8 4 5 20 585 1  
 9 7 4 28 569 1  
 10 7 4 28 569 1  
 11 4 5 20 585 1  
 12 3 3 21 709 1  
 1 7 3 15 608 2  
 2 8 5 28 643 2  
 3 8 5 28 643 2  
 4 8 5 28 643 2  
 5 8 5 28 643 2  
 6 7 3 15 608 2  
 7 7 3 21 805 2  
 8 4 5 20 661 2  
 9 7 4 20 719 2  
 10 7 4 20 719 2  
 11 4 5 20 661 2  
 12 7 3 21 805 2  
 1 7 3 11 693 3  
 2 8 5 20 678 3  
 3 8 5 20 678 3  
 4 8 5 20 678 3  
 5 8 5 20 678 3  
 6 7 3 11 693 3  
 7 7 3 21 978 3  
 8 4 5 15 826 3  
 9 7 4 20 134 3  
 10 7 4 20 134 3  
 11 4 5 15 826 3  
 12 7 3 21 978 3  
 1 7 3 15 608 4  
 2 8 5 28 643 4  
 3 8 5 28 643 4  
 4 8 5 28 643 4

(Continued)

Table VI.21 (Continued)

5	8	5	28	643	4
6	7	3	15	608	4
7	7	3	21	805	4
8	4	5	20	641	4
9	7	4	20	719	4
10	7	4	20	719	4
11	4	5	20	661	4
12	7	3	21	805	4
1	7	3	13	593	5
2	8	5	24	681	5
3	8	5	24	681	5
4	8	5	24	681	5
5	8	5	24	681	5
6	7	3	13	593	5
7	7	3	18	964	5
8	4	5	17	784	5
9	7	4	17	972	5
10	7	4	17	972	5
11	4	5	17	784	5
12	7	3	18	964	5
1	7	3	15	608	6
2	8	5	28	643	6
3	8	5	28	643	6
4	8	5	28	643	6
5	8	5	28	643	6
6	7	3	15	608	6
7	7	3	21	805	6
8	4	5	20	661	6
9	7	4	20	719	6
10	7	4	20	719	6
11	4	5	20	661	6
12	7	3	21	805	6
1	7	3	14	614	7
2	8	5	26	668	7
3	8	5	26	668	7
4	8	5	26	668	7
5	8	5	26	668	7
6	7	3	14	614	7
7	7	3	20	851	7
8	4	5	19	695	7
9	7	4	19	805	7
10	7	4	19	805	7
11	4	5	19	695	7
12	7	3	20	851	7
1	7	3	15	608	8
2	8	5	28	643	8
3	8	5	28	643	8
4	8	5	28	643	8
5	8	5	28	643	8
6	7	3	15	608	8
7	7	3	21	805	8
8	4	5	20	661	8
9	7	4	20	719	8
10	7	4	20	719	8
11	4	5	20	661	8
12	7	3	21	805	8

(Continued)

Table VI.21 (Continued)

```

1 7 3 15 625 9
2 8 5 27 652 9
3 8 5 27 652 9
4 8 5 27 652 9
5 8 5 27 652 9
6 7 3 15 625 9
7 7 3 20 831 9
8 4 5 19 682 9
9 7 4 20 758 9
10 7 4 20 758 9
11 4 5 19 682 9
12 7 3 20 831 9
SWEEP = 9 FAILED BACK-UP TO SWEEP = 8
DELETION TERMINATED PERDOLT ) PDHN
NO OF PILES = 264
EXCESS PLF = 0
MAX DISPL = 4481E+00 1042E+00 4280E+00
PFCOST = 264000.00
OBTAINED BY DELETING THE MOST LOADED PILES
TIME REQUIRED FOR THIS DELETION = 5.235

```

ZONE NO 10 IS A REPEAT OF ZONE NO 9

ZONE NO 11 IS A REPEAT OF ZONE NO 8

ZONE NO 12 IS A REPEAT OF ZONE NO 7

#### CPU TIME

OPTIMUM BATTER SLOPE PHASE 193 967 SECONDS  
PILE DELETION PHASE 208 585 SECONDS

#### \*\*\*\*\* OPTIMIZATION RESULTS \*\*\*\*\*

OPTIMUM PILE FOUNDATION COST = 198000 00

ZONE NO	OPTIMUM SPACINGS	OPTIMUM BATTER SLOPES
	SPA-1 SPA-2 H-1 H-2	
1	48000E+02 24000E+02	20401E+01 - 21008E+01
2	42000E+02 36000E+02	- 21621E+01 20081E+01
3	42000E+02 36000E+02	- 21621E+01 20081E+01
4	42000E+02 36000E+02	- 21621E+01 20081E+01
5	42000E+02 36000E+02	- 21621E+01 20081E+01
6	48000E+02 24000E+02	20401E+01 - 21008E+01
7	48000E+02 24000E+02	21265E+01 20000E+01

(Continued)

Table VI.21 (Continued)

8	60000E+02	36000E+02	38953E+01	20000E+01
9	48000E+02	36000E+02	86342E+01	20000E+01
10	48000E+02	36000E+02	86342E+01	20000E+01
11	60000E+02	36000E+02	38953E+01	20000E+01
12	48000E+02	24000E+02	21265E+01	20000E+01

PLACEMENT OF PILES IN ZONES

PILES WERE DELETED FROM ZONE 1  
AT GRID PT I, J

1 1  
1 3  
2 1  
2 3  
3 1  
3 3  
5 2  
6 2  
7 2

ZONE 1 HAS 7 ROWS, 3 COLS, 12 PILES WITH 9 DELETED.

PILES WERE DELETED FROM ZONE 2  
AT GRID PT I, J

1 2  
1 3  
1 5  
2 2  
2 3  
2 5  
3 2  
3 3  
3 5  
4 2  
4 3  
4 5  
5 1  
6 1  
6 4  
7 1  
7 4  
8 1  
8 2  
8 4

ZONE 2 HAS 8 ROWS, 5 COLS, 20 PILES WITH 20 DELETED

PILES WERE DELETED FROM ZONE 3  
AT GRID PT I, J

1 2  
1 3

(Continued)

Table VI.21 (Continued)

1 5  
2 2  
2 3  
2 2  
3 3  
3 3  
4 2  
4 3  
4 3  
4 5  
5 1  
6 1  
6 4  
7 1  
7 4  
8 1  
8 2  
8 4

ZONE 3 HAS 8 ROWS, 5 COLS, 20 PILES WITH 20 DELETED

PILES WERE DELETED FROM ZONE 4  
AT GRID PT 1, J

1 2  
1 3  
1 5  
2 2  
2 3  
2 5  
3 2  
3 3  
3 5  
4 2  
4 3  
4 5  
5 1  
6 1  
6 4  
7 1  
7 4  
8 1  
8 2  
8 4

ZONE 4 HAS 8 ROWS, 5 COLS, 20 PILES WITH 20 DELETED

PILES WERE DELETED FROM ZONE 5  
AT GRID PT 1, J

1 2  
1 3  
1 5  
2 2  
2 3  
2 5

(Continued)

23523511414124  
33344456677888

ZONE 5 HAS 8 ROWS, 5 COLS, 20 PILES WITH 20 DELETED.

FILES WERE DELETED FROM ZONE 6  
AT GRID PT I, J

1 3 1 3 1 3 2 2 2  
1 1 2 2 3 3 4 4 7

ZONE 6 HAS 7 ROWS, 3 COLS. 12 PILES WITH 9 DELETED.

PILES WERE DELETED FROM ZONE 7  
AT GRID PT I, J

— 2 —

ZONE 7 HAS 7 ROWS, 3 COLS, 19 PILES WITH 2 DELETED

PILES WERE DELETED FROM ZONE 8  
AT GRID PT I, J

1 2 3 4 5 1 3  
1 1 1 1 1 3 3

ZONE 3 HAS 4 ROWS, 5 COLS. 13 PILES WITH 7 DELETED

PILES WERE DELETED FROM ZONE 9  
AT GRID PT 1, J

(Continued)

(Continued)

Table VI.21 (Continued)

1 5  
3 1  
3 3

ZONE 11 HAS 4 ROWS, 5 COLS, 13 PILES WITH 7 DELETED

PILES WERE DELETED FROM ZONE 12  
AT GRID PT I, J

4 1  
4 2

ZONE 12 HAS 7 ROWS, 3 COLS, 19 PILES WITH 2 DELETED

TOTAL NUMBER OF PILES = 198

SOIL CONDITION NO 1  
STIFFNESS MATRIX S  
1445E+05 0 2118E+04 0 1237E+05 - 1304E-07 - 6917E+07 5355E-08  
0 1237E+05 0 2118E+04 0 6999E+05 6519E-07 - 2614E+08 7721E+06  
- 1304E-07 0 6519E-07 1158E+11 - 8583E-05 - 3029E+10 1304E-07  
- 6917E+07 0 - 2614E+08 - 1049E-04 1237E+11 7629E-05  
5355E-08 7721E+06 1304E-07 - 3029E+10 1621E-04 3160E+10  
FLEXIBILITY MATRIX F  
9764E-04 1846E-18 1485E-04 - 2826E-22 8598E-07 - 5065E-21  
3210E-18 5358E-03 7541E-18 - 4569E-07 1970E-20 - 1747E-06  
1485E-04 5063E-18 6999E-04 - 5991E-21 1562E-06 - 1389E-20  
- 1403E-21 - 4569E-07 - 8027E-21 1191E-09 - 1836E-23 1254E-09  
8598E-07 1242E-20 1562E-06 - 1258E-23 4589E-09 - 3407E-23  
- 8808E-21 - 1747E-06 - 2069E-20 1254E-09 - 5405E-23 4793E-09

RESULTS FOR SOIL CONDITION NO 1

LOAD CASE	PILE CAP DISPLACEMENTS							DMAX
	U1	U2	D3	D4	D5	D6	D6	
1	- 363E+00	109E-14	319E+00 - 313E-17	- 189E-03 - 299E-17	- 299E-17	- 299E-17	- 299E-17	581E+00
2	535E+00	867E-15	187E+00 - 117E-17	- 123E-03 - 238E-17	- 238E-17	- 238E-17	- 238E-17	601E+00
3	545E+00	172E-14	270E+00 - 211E-17	- 476E-04 - 472E-17	- 472E-17	- 472E-17	- 472E-17	609E+00
4	202E+00	134E-14	211E+00 - 188E-17	- 368E-04 - 368E-17	- 368E-17	- 368E-17	- 368E-17	292E+00
5	238E+00	154E-14	211E+00 - 192E-17	- 142E-03 - 422E-17	- 422E-17	- 422E-17	- 422E-17	318E+00
6	238E+00	831E-01	211E+00 - 217E-03	- 228E-03 - 448E+00	- 448E+00	- 448E+00	- 448E+00	448E+00

FOR SOIL CONDITION NO 1 SUM OF PLF = 18397E+03

(Continued)

Table VI.21 (Concluded)

PILE FOUNDATION COST = 198000 00

ARRAY A(NMAX) CONTAINED 599 WORDS

## REFERENCES

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2. Saul, W. E., "Static and Dynamic Analysis of Pile Foundations", Journal of the Structural Division, ASCE, Vol. 94, No. ST5, Proc. Paper 5936, May, 1968, pp.1077-1100.
3. LMVD Pile Report - U. S. Army Engineer Waterways Experiment Station, Unpublished Report, 1977.
4. Murray, W., Numerical Methods for Unconstrained Optimization, Academic Press, London, 1972, pp.26-28.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Hill, James L

User's guide : Computer program for optimal design and analysis of pile foundations (PILEOPT) : final report / by James L. Hill, Systems Engineering Consultants, Inc., Tuscaloosa, Ala. ; prepared for U.S. Army Engineer Division, Lower Mississippi Valley ; monitored by Automatic Data Processing Center, U.S. Army Engineer Waterways Experiment Station. -- Vicksburg, Miss. : U.S. Army Engineer Waterways Experiment Station ; Springfield, Va. : available from NTIS, 1981.

161 p. : ill. ; 27 cm. -- (Instruction report / U.S. Army Engineer Waterways Experiment Station ; K-81-5)

Cover title.

"March 1981."

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1. Foundations. 2. Mathematical analysis. 3. PILEOPT (Computer program). 4. Piling (Civil engineering). 4. Programming (Electronic computers). I. Systems Engineering Consultants. II. United States. Army. Corps of Engineers. Lower Mississippi Valley Division.

Hill, James L

User's guide : Computer program for optimal : ... 1981.  
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III. United States. Army Engineer Waterways Experiment Station. Automatic Data Processing Center. IV. Title V. Series: Instruction report (United States. Army Engineer Waterways Experiment Station) ; K-81-5.  
TA7.W34i no.K-81-5